Enhancement of drift waves by localized lower hybrid waves

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The enhancement of low frequency oscillations by lower hybrid waves at electric fields lower than the thresholds of other parametric decay processes is presented. The frequencies and wavelengths of these oscillations agree with the collisional drift wave dispersion relation. The enhancement is localized deep inside the plasma density gradient. The excited drift waves change the density profile and the lower hybrid wave trajectory.

I. INTRODUCTION

The possibility of heating magnetized plasma by lower hybrid waves[1] has been actively investigated in recent years. Excitation and penetration of the waves into the interior of the plasma were successfully demonstrated by using slow wave structures.[2,3] One important question concerning any rf heating technique is whether the rf power will couple to low frequency drift waves; these can enhance anomalous transport and so reduce the overall heating efficiency. Recent laser scattering experiments[4] in the ATC tohamak shows that rf heating can enhance density fluctuations at the plasma edge. Therefore, it is important to investigate in more detail the effects of rf electric fields on low frequency drift waves in small scale experiments in which local plasma parameters can easily be measured. The mixing of low frequency oscillations and $\omega_0 \sim \omega_{lh}$ rf electric fields was first reported by Hooke *et al.*,[5] but the low frequency oscillations were not identified and the interaction between the high and low frequency oscillations was not studied in detail. The generation of drift waves by lower hybrid fields was also studied in a pulsed experiment by Baranov *et al.*[6] In that experiment, the plasma was created and sustained by the large amplitude rf electric field. Therefore, the plasma equilibrium changed with rf power and magnetic field strength, and it was not clear whether the drift wave was excited by the rf or just a natural consequence of the plasma equilibrium. In Sec. II of this paper, we present experimental observations showing that relatively small amplitude lower hybrid waves can excite drift waves causing enhanced cross field transport. The excitation mechanism will be discussed in Sec. III and a short summary and conslusion will be given in Sec. IV.

II. EXPERIMENTAL OBSERVATION

The experiments were performed in the Princeton L-3 device in the density range $5\times10^9/\text{cc} < n_0 < 5\times10^{10}/\text{cc}$, magnetic field $B \simeq 1.3$ kG, in helium plasma with $T_i < 0.1$ eV, $T_e < 3$ eV, neutral pressure $\simeq 1$ mTorr. Figure 1 shows a simplified schematic of the experimental setup. The plasma was produced by tungsten filament source.[7] The lower hybrid waves were excited by a 1 m long slow wave structure consisting of eight alternately phased rings driven by an rf oscillator. The detailed features of the antenna and the machine have been described previously.[2,8] Probes No. 1 and No. 3 located in the density gradient region ($r \sim 3.2$ cm) gave the low frequency density and potential oscillations. These are spontaneously excited drift waves the spectrum of which varies with the plasma equilibrium.

The drift wave spectrum is changed when rf power is applied to the slow wave structure to excite lower hybrid waves. Figure 2 shows the variation of the low frequency oscillation spectrum as a function of the rf oscillator voltage. The various peaks in Fig. 2 correspond to the different azimuthal mode numbers, m. Typical raw data from which m was deduced are shown in Fig. 3. This was obtained by connecting a 360° scanning azimuthal probe (No. 3) and a stationary reference probe (No. 1) to a narrow-band interferometer. At low rf voltages (≤ 5 V P – P), the $m = 5$ mode dominates. The radial and axial wavenumbers ($k_r \sim 0.8$ cm^{-1}, $k_z \sim 4\times10^{-3}$ cm^{-1}) were measured from phase shifts between probes at different radial and axial positions. Since the waves are not very coherent, a boxcar integrator is used as a sampling scope in the phase shift measurements to average out the fluctuations. It is interesting to note that the data shown in Fig. 3 resemble Hooke and Bernabei's[9] result. This apparent resemblance is because the same technique (interferometry by a rotating azimuthal probe) was used to measure the azimuthal mode number m. Hooke and Bernabei observed ion-acoustic waves propagating in the azimuthal direction with the acoustic speed C_s, and we observed drift waves propagating with the diamagnetic velocity which is ten times lower than C_s; therefore, they are totally different waves.

As the rf power increases, more modes are excited. A narrow-band-pass filter was used to select a partic-

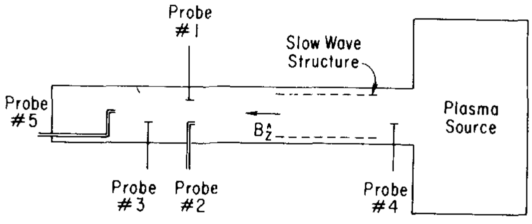

FIG. 1. Schematic of experimental setup.

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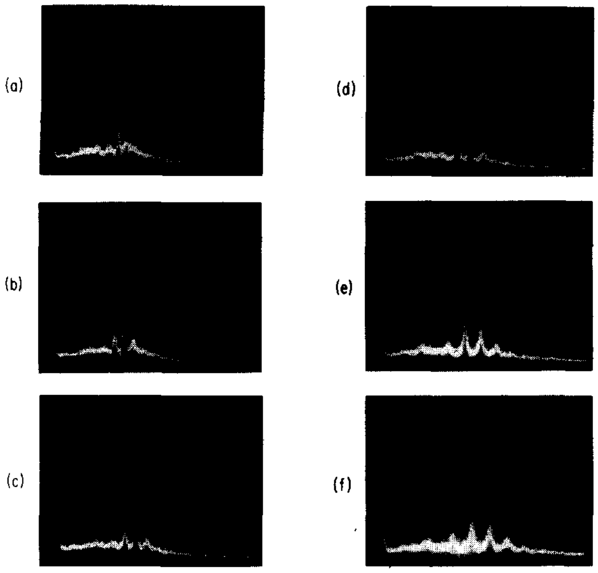

FIG. 2. Drift wave spectrum (0–50 kHz) as a function of rf voltage. The rf frequency is 20 MHz. The plasma density is about 10^{10}/cc at the center of the plasma column.

ular mode for interferometry measurements. For $m \geq 3$, the m number always corresponds to the mth peak in the spectrum. The amplitude of the first two peaks are not large enough for interferometry. They are conjectured to be the $m=1$ and $m=2$ modes. Figure 4 shows the frequencies of different m modes measured in the laboratory frame of reference. To correct for the $\mathbf{E}\times\mathbf{B}$ rotational Doppler shift, one can estimate the radial electric field from the ambipolar diffusion equations and get[6]

$$\mathbf{E} = -\frac{T_e \nu_e m_e - T_i \nu_i m_i}{e\nu_e m_e + e\nu_i m_i}\frac{\nabla n}{n_0}$$

$$\simeq \frac{T_i}{e}\frac{\nabla n}{n_0} \lesssim -0.1 \text{ V/cm rad}. \quad (1)$$

Therefore, the Doppler shift correction is insignificant ($\lesssim 10\%$) due to the low ion temperature ($T_i < 0.1$ eV). The measured frequencies are compared with the values calculated from the collisional drift wave dispersion relation[10] for $T_i \ll T_e$, $\omega \ll \omega_{ci}$

$$b\,\omega^2 + \frac{i}{t_\parallel}(1+b)\,\omega - i\frac{\omega^*}{t_\parallel} = 0. \quad (2)$$

Here, $b = (k_\theta^2 + k_r^2)C_s^2/\omega_{ci}^2$

$t_\parallel = m_e \nu_e / k_z^2 T_e$,

$$\omega^* = k_\theta v_{de} = k_\theta \frac{CT_e}{eB}\frac{(-dn_0/dr)}{n_0}.$$

Figure 4 shows the m dependence of ω predicted by Eq. (2). The values of $-n_0/(dn_0/dr) = 1.5$ cm and $r = 3.2$ cm used for the theoretical curves were measured experimentally. The electron temperature at $r = 3.2$ cm was measured to be 2 eV. Because of the uncertainties in the probe measurements, theoretical curves for $T_e = 1.5$ eV and $T_e = 3$ eV are also shown in Fig. 4 (dotted lines). These theoretical curves are in reasonable agreement with the experimental measurements (dots and circles). At high rf power, all the modes

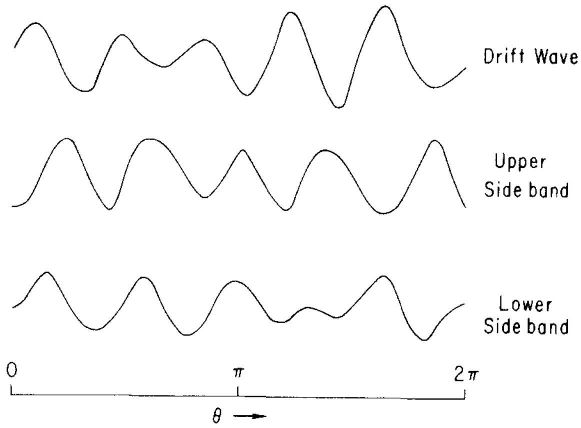

FIG. 3. Interferogram for determination of the azimuthal mode number m of the drift waves and the sidebands.

with $m \leq 6$ are excited and there is an upshift in frequency for each mode as shown by the dots in Fig. 4(a). Figure 4(b) shows that the drift wave frequencies vary linearly with the rf voltage.

The rings used to excite the lower hybrid waves are usually floating and, hence, may have some dc voltage on them. To insure that the drift waves are not excited

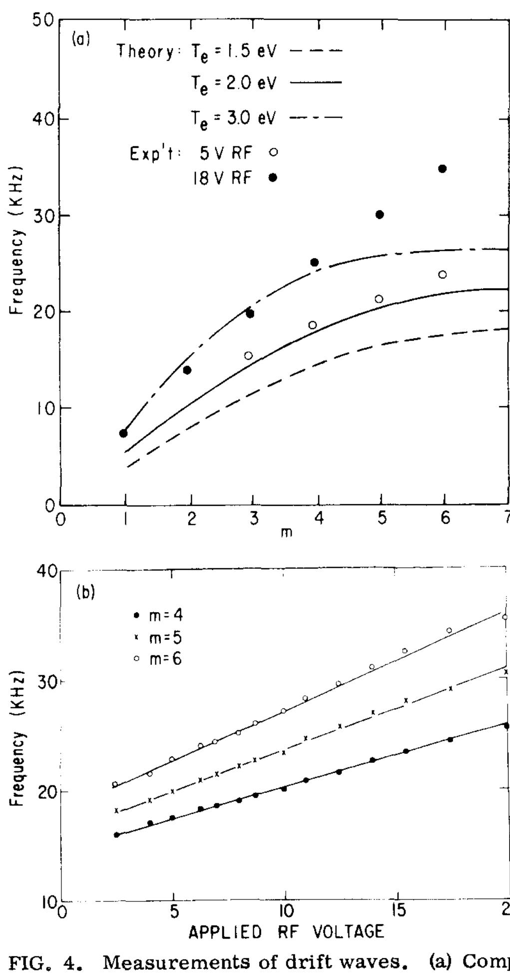

FIG. 4. Measurements of drift waves. (a) Comparison of measured and calculated drift wave frequencies, (b) Drift wave frequency as a function of rf voltage.

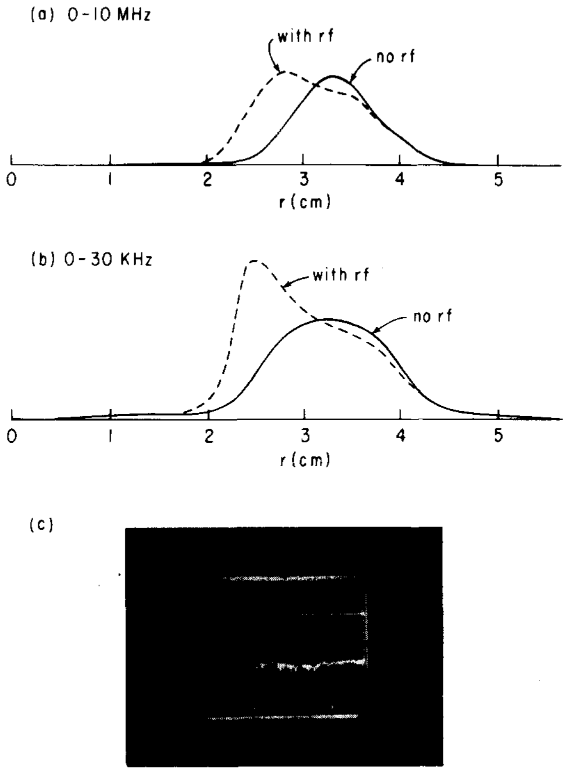

FIG. 5. Density fluctuations excited by lower hybrid waves. (a) Radial profile of density fluctuations (0–10 MHz) with and without rf, (b) radial profile of density fluctuations (0–30 kHz) with and without rf, (c) increase of oscillation amplitude induced by a 5 msec, 20 MHz, 10 V rf pulse. The top trace is the rf pulse and the bottom trace is the density oscillation observed by a Langmuir probe at $r \simeq 2.5$ cm.

by the dc voltage on the rings, a 39 μH rf choke is connected to each ring to provide a dc ground and the same oscillation spectrum appears when rf is applied. The rf field causes significant changes in the drift wave spectrum as well as amplitude. The amplitude change depends on the radial position. The increase in amplitude is mainly localized at the inside edge of the density gradient as shown in Fig. 5(a) where the amplitude was measured by a wideband (0–10 MHz) voltmeter. The increase in oscillation amplitude mainly occurs for oscillations with frequency approximately equal to 20 kHz. Using the spectrum analyzer as a 30 kHz bandwidth voltmeter, the change in oscillation amplitude in this frequency range is shown in Fig. 5(b). By pulsing the rf and watching the oscillation amplitude on an oscilloscope, one can see that the amplitude can increase by a factor of three, as shown in Fig. 5(c).

Figure 6 shows the spectrum of the lower hybrid pump and the sidebands when the $m = 5$ mode drift wave is excited. The frequency separation between the pump and the sidebands is always the same as the drift wave frequency. Interferometry measurements indicate that both sidebands have $m = 5$ as shown in Figs. 3(b) and 3(c). The sidebands are localized inside the lower hybrid wave packet. The amplitude of the lower sideband is only 20%–30% higher than the upper sideband. These indicate that the sidebands mainly come from the amplitude modulation of the pump.

Coincident with the onset of the excited drift waves, the plasma density profile changes as shown in Fig. 7(a). The density decreases in the central part and increases in the outer part of the plasma column indicating enhanced cross-field transport.[11] The change in density profile modifies the lower hybrid wave trajectory. At the same axial position, the lower hybrid wave packet shifts toward the center of the plasma column at high rf power, as shown in Fig. 7(b). All these things happen before other parametric decay activities; in other words, they happen at electric fields lower than the thresholds of other parametric decay processes.[12,13]

III. ENHANCEMENT MECHANISM

The experimental observations indicate that externally launched lower hybrid waves can change the drift wave spectrum and amplitude as well as the plasma equilibrium. It is important to find out whether it is the change in plasma equilibrium that causes the drift waves or vice versa. With lower hybrid waves on, the density scale length increases. This should make the drift wave more stable. In other words, the change in density profile should be the consequence rather than the cause of the drift waves. One possibility is electron heating; since the diamagnetic drift velocity is proportional to the electron temperature, an increase in electron temperature can provide more free energy to drive the drift waves. To check this possibility, the electron temperature profile was measured at different rf power levels. In the presence of an rf electric field, Langmuir probe I-V characteristics became difficult to interpret; therefore the test wave technique was used. A T-tip probe was used to launch a small amplitude electrostatic ion cyclotron wave which obeyed the dispersion relation $\omega^2 = \omega_{ci}^2 + k^2 c_s^2$. The wavelengths at different frequencies were measured by interferometry. By plotting ω^2/ω_{ci}^2 vs k^2, a straight line was obtained which passed through (1, 0). This verifies the dispersion relation. The slope of the line determines the electron temperature. The spatial resolution of this technique is limited by the wavelength of the test wave

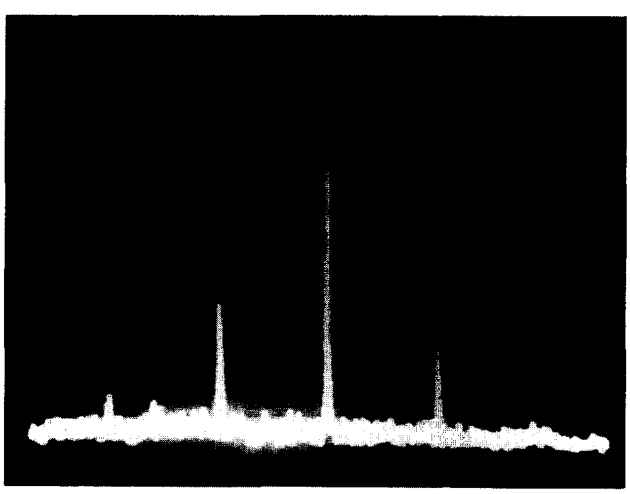

FIG. 6. Spectrum of the pump and the sidebands observed by a T-tip probe at $r \simeq 3.2$ cm.

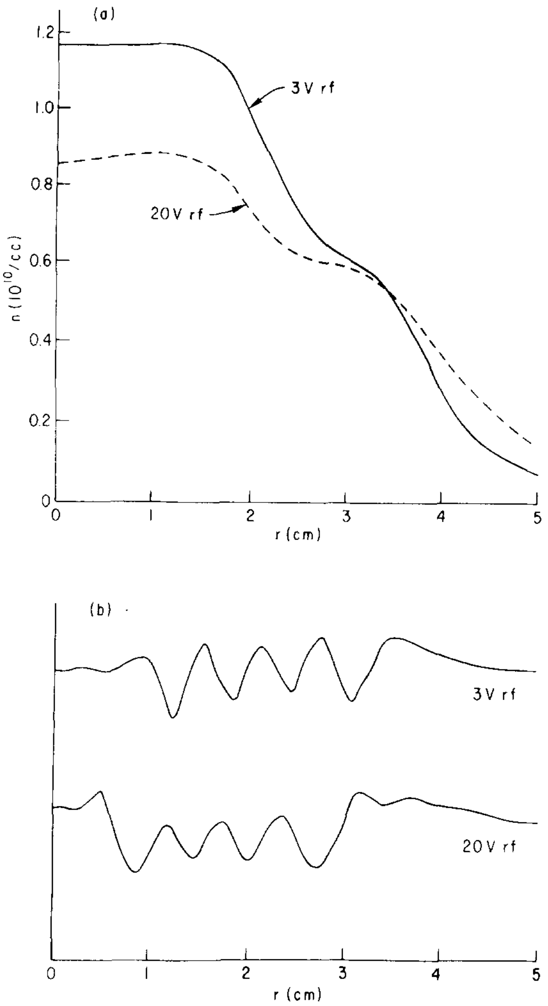

FIG. 7. Density profile modified by lower hybrid waves. (a) Variation of density profile with rf amplitudes, (b) Variation of the lower hybrid wave packet position with rf amplitude.

which is about 0.5 cm. The schematic of the test wave setup and some typical data are shown in Fig. 8(a). Figure 8(b) shows the change in electron temperature due to a large amplitude lower hybrid wave (15 V, 20 MHz). However, it was found that the drift wave activities occurred even for low powers where no heating was observed. This indicates that it is not the electron heating that excites the drift waves.

To find an explanation for the experiment, one can look into the theory of parametric instabilities. It is well known that the dispersion relation of drift waves can be strongly modified by external high frequency electric fields.[14] Sundarum and Kaw,[15] using the dipole approximation, studied the parametric excitation and suppression of drift waves by electric fields near lower hybrid frequency ω_{lh} and found that the rf electric field (of frequency ω_0) had the tendency to suppress drift waves when $\omega_0 > \omega_{lh}$. In most of the present experiments, low frequency ($\omega \ll \omega_{ci}$) drift waves have wavelengths longer than the lower hybrid waves, and the dipole approximation is not appropriate; unfortunately, a finite wavelength theory does not exist. If the lower hybrid wavenumber k_0 is less than the drift wavenumber k, then the results from dipole approximation can still be used with some modification in the coupling coefficient. The change in the coupling coefficient is of the order of k_0/k. In our experiment $k_0/k \gg 1$. We are in the geometrical optics regime, and the results from the dipole approximation cannot be applied. It should be noted that the parallel wavelength of the drift wave is longer than the lower hybrid wave packet and the drift wave excitation is not localized inside the lower hybrid wave packet. This is not surprising because the drift waves are normal modes of the plasma and therefore can be excited by a localized driving force. One simple analogy is a vibrating string. Waves in a string can be excited by perturbing one point in the string. When a single ring or a number of rings are driven in phase to launch a more localized lower hybrid resonance cone, similar drift wave activities can be excited at power levels higher than that with a lower hybrid wave packet. This is again not surprising because a resonance cone is just a superposition of lower hybrid waves with a broad k spectrum. The maximum rf electric field in the resonance cone can be measured by a calibrated double-tip probe. It is always less than 3 V/cm which is much weaker than that required for soliton formation.

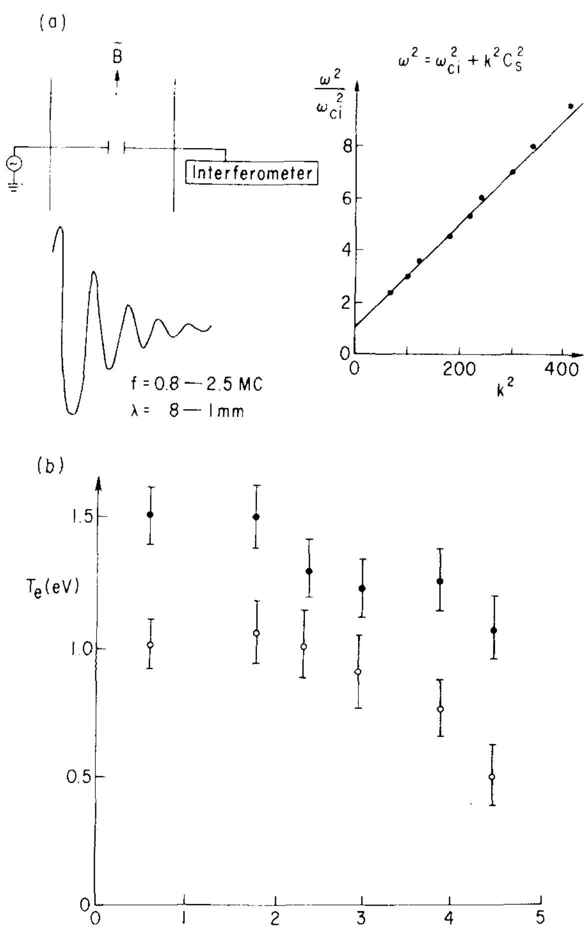

FIG. 8. Electron temperature measurements. (a) Measurement of electron temperature profile by test wave technique. (b) Electron temperature profiles with (dots) and without (open circle) rf (15 V, 20 MHz).

IV. SUMMARY

In this paper, we report experimental observation of drift wave enhancement by externally launched lower hybrid waves. The enhancement is mainly localized at the inner edge of the density gradient, behind the natural drift waves. The excited drift waves enhance cross-field transport, change the density profile, and the lower hybrid wave trajectory. These can happen at electric fields lower than the thresholds of other parametric decay instabilities.

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