quency, this results from Eq. (1) in longer wavelengths and larger phase velocities. Electrons are then untrapped from the lower-velocity region of the trapped vortices, resulting in a positive source term from Eq. (2) as indicated in the discussion of case (b). In effect, electrons are untrapped after losing their kinetic energy to the potential energy of the wave, thus maintaining the amplitude of the potential wells as they advance to the front of the wave packet.

In the computer runs described above we do not expect the trapped-particle instability[6] to appear since even for case (c), the sideband e-folding time $\tau_s = 18\omega_p^{-1}$ is not much less than the resonant particle transit time $\tau_{tr} = 2\bar{x}/v_A = 26\omega_p^{-1}$. For wave packets which satisfy $\tau_s/\tau_{tr} \ll 1$, it appears quite likely that the collective oscillations of the trapped particles will result in additional density modulation. Finally, we wish to remark that the lengthening of the wave packet by the dressed trapped particles may be viewed as a process which generates "clumps" or "macroparticles" invoked by Dupree in his theory of turbulent resistivity.[7]

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Direct Observation of Waves Propagating near the Lower-Hybrid-Resonance Frequency*

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Electrostatically driven oscillations near the lower-hybrid-resonance frequency have have been studied in a linear plasma device. The index of refraction of these waves is measured directly and is seen to peak at a critical density as the wave propagates radially inward. A strong, nonlinear interaction is observed between the driven oscillations and the low-frequency drift-wave–like fluctuations which exist in this plasma.

The possibility of heating plasma at frequencies near the lower hybrid resonance has been recognized for a number of years.[1] At the University of Texas, experimental and theoretical studies of the loading of an rf coil have been reported in detail in a series of papers.[2] Golant and his coworkers have done experimental[3] and theoretical[4] work on the linear-mode conversion effect emphasized in Ref. 1. Recently several workers have obtained evidence of plasma heating near the lower-hybrid-resonance frequency.[3,5] A fundamental reason for interest in this resonance is the possibility of heating plasmas in large thermonuclear devices at the lower-hybrid-resonance frequency. The term "lower hybrid resonance" refers to a singularity in the index of refraction which occurs, for cold unbounded plasmas, at

$$\frac{\omega_{LH}^2 = \omega_{ci} + \omega_{pi}}{1 + (\omega_{pi}^2 + \omega_{ci}^2)/\omega_{ci}\omega_{ce}} \quad (1)$$

if the angle θ between the wave vector $\vec{k}$ and the magnetic field $\vec{B}$ is sufficiently close to 90° to satisfy the relation

$$\cos^2\theta = k_\parallel^2/(k_\parallel^2 + k_\perp^2) \ll m_e/m_i. \quad (2)$$

Here ω_{ci} and ω_{ce} are the ion and electron cyclotron frequencies, and m_i, m_e, and ω_{pi}, ω_{pe} are the particle masses and plasma frequencies, and $k_\parallel$ and $k_\perp$ are the components of $\vec{k}$ parallel and perpendicular to $\vec{B}$.

Skipping, Oakes, and Schluter[6] have made a detailed theoretical study of coil loading near the lower-hybrid-resonance frequency. In this work they emphasize the difficulty of distinguishing between the lower-hybrid and coupling resonances. A coupling resonance involves the generation of a natural mode in a plasma column of finite diameter. Resonances associated with the finite plasma diameter D_p have been studied in great detail by Messiaen, Monfort, and Vandenplas.[7] For the fundamental radial mode in a coupling resonance, $k_\perp \approx 2\pi/D_p$ which for most wave-damping processes is too small to achieve ion heating.

In all of the experiments reported so far, $\lambda_0 \gg D_p$, and many, if not all, of the reported effects could conceivably result from coupling resonances. Furthermore, there has been no direct experimental observation of the index of refraction of waves propagating near the lower-hybrid-resonance frequency.

The purpose of this experiment is to measure the index of refraction directly under experimental conditions such that $\omega \approx \omega_{LH}$.

The oscillations are generated electrostatically by a balanced rf system which drives the plates shown in Fig. 1(a). A doubly shielded (i.e., triaxial) electrostatic probe travels in the radial direction and is used to detect the plasma waves. The generating and detecting systems are electrostatic, since the waves generated here are basically electrostatic in nature. The T-shaped probe is used merely to increase the probe-tip area in order to enhance the rf signal. The rf signal from the probe is fed, together with a reference signal, into an amplitude-insensitive interferometer system which gives the phase Φ as a function of the radial position of the probe. For the case of traveling waves with no reflections, we have $\Phi = \int^r k_\perp dr$, where $k_\perp$ is the local wave number and r is the radial probe position. The local index of refraction can be computed from $n_\perp(r) = (c/\omega)k_\perp(r) = (c/\omega)\,d\Phi/dr$.

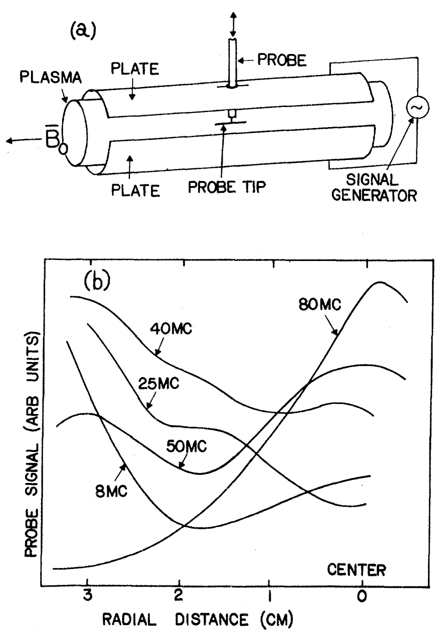

FIG. 1. (a) Schematic of experimental setup. The doubly shielded probe moves radially through a hole in the wave generating plate. The plates are insulated from the plasma by a glass cylinder. (b) Amplitude of the rf signal detected by the probe. The signal is measured with a spectrum analyzer which drives a chart recorder.

The plate length L_P is made rather long (70 cm) in the direction parallel to $\vec{B}$, since, in order to satisfy Eq. (2), we make $k_\parallel$ as small as possible. The Fourier spectrum of the driving field gives

$$k_\parallel \lesssim \pi/L_P. \quad (3)$$

The plasma in this linear device is generated by a "Lisitano coil"[8] operating at 2.45 GHz. The magnetic field is typically 1200 G, and the peak electron density ranges up to about 2×10^{11} cm^{-3}. The electron temperature varies between 5 and 10 eV, and the ion temperature is of the order of 1 eV. The dominant collisional process is electron-neutral, and the neutral pressure is typically 2×10^{-3} Torr so that $\omega\tau_{\mathrm{collision}} \approx 50$. The absolute value of the electron density is obtained from an 8-mm microwave interferometer.

Figure 1(b) shows the amplitude of the rf signal as a function of radius. The experimental conditions are such that for $f \lesssim 35$ MHz the waves encounter a density where $\omega = \omega_{LH}$. At higher frequencies $\omega > \omega_{LH}$, the resonance condition is not satisfied, and experimentally we see an increased radial penetration and even an amplitude maximum in the center of the plasma. This center-peaked distribution is exactly what one expects for a coupling resonance.

Results of the interferometer measurements are shown in Fig. 2(a). The index of refraction is immeasurably small near the plasma surface, but rapidly approaches a maximum at a particular radial position. The dashed curves show that for a less dense plasma the point of maximum index of refraction moves radially inward until the local density is approximately the same as for the higher-density case. We equate equal ion saturation currents with equal densities, since the electron temperature difference in the two cases is negligibly small. These data indicate that for a fixed frequency and magnetic field the point of peak index of refraction is determined by a critical value of the density. The value of the density obtained from Eq. (1) for this case agrees, within a factor of 2, with the density measured with the microwave interferometer and Langmuir-probe measurements. If we take the estimated value of $k_\parallel$ from Eq. (3) together with

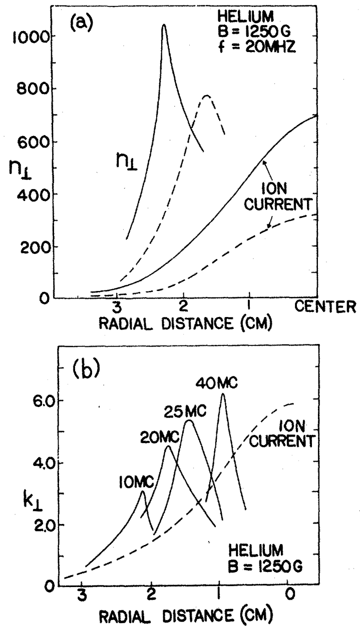

FIG. 2. (a) Index of refraction versus radial position for two different plasma densities. The solid (dashed) index-of-refraction curves correspond to measurements made with the solid (dashed) radial-density-distribution curves. (b) Perpendicular wave number versus radial position for several frequencies.

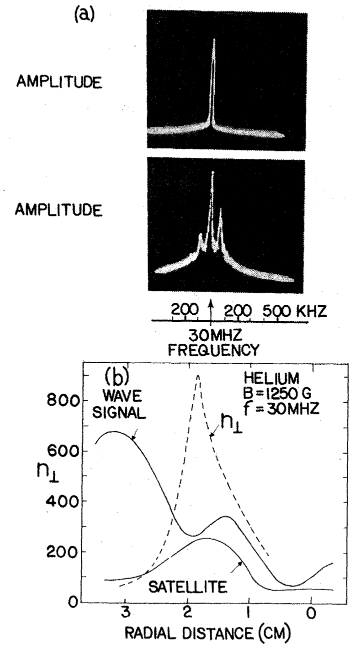

FIG. 3. (a) Frequency spectrum of the driven plasma oscillations near the plasma surface (top) and in the plasma near the region of critical density (bottom). (b) The index of refraction, the wave amplitude, and the satellite amplitude as a function of radial position.

the maximum measured value of $k_\perp$, we see that $\cos^2\theta \sim \frac{1}{5}(m_e/m_i)$ and the inequality (2) is approximately satisfied. The physical effect leading to the finite value of $k_\perp$ at resonance is being studied.

We have observed that the direction of the phase velocity of these waves points from the center of the plasma *toward* the wave-generating plates. It is easily shown that in the radial direction this mode is a backward wave; and if energy is flowing from the plates to the plasma, we should observe the phase velocity of the waves to be directed radially outward as seen in these experiments.

Figure 2(b) shows plots of the local perpendicular wave number versus radial position for several different frequencies. As predicted by Eq. (1), the critical density n_c increases with frequency. However, the rate of increase is not as rapid as that predicted from Eq. (1). The experimentally observed critical density agrees with this relation within a factor of 2 for the lower frequencies, but as the frequency increases, the discrepancy between the observed and predicted density increases to as much as a factor of 8. Equation (1), however, comes from the theory for cold, uniform, finite, collisionless plasmas. These relations cannot adequately describe the present experiment and we are, therefore, developing a more comprehensive theory. The important point here is that a resonance-like behavior is observed in the refractive index even though we are working with free-space wavelengths many times greater than the plasma diameter. We conclude that it is possible to generate a plasma resonance even though $\lambda_0 \gg D_p$, and that many of the previously reported experimental effects may come from achieving a genuine lower hybrid resonance rather than a coupling resonance.

Furthermore, most of the wave energy appears to be absorbed rather than reflected. Occasionally we see rapid changes in phase shift every 180° as the wave moves radially inwards. This rapid change is expected if there is some wave reflection. In general, however, we see no evidence for reflection over the entire range of about 700° of phase shift.

An interesting phenomenon observed near the position of peak index of refraction is shown in Fig. 3(a). Near the outside edge of the plasma the frequency spectrum of the oscillation is relatively narrow and is similar to that of the driving oscillator as shown in the top half of Fig. 3(a). As the probe is moved radially inward the wave spectrum develops the satellites shown in the bottom of Fig. 3(a). These satellites are shifted by approximately 70 to 100 kHz from the oscillator frequency. Near the region of maximum refractive index the amplitude of the satellites grows and becomes nearly equal to that of the central peak. Figure 3(b) shows simultaneous values of the index of refraction, the wave amplitude, and the satellite amplitude as a function of radial position.

There are oscillations in this plasma which modulate the density by about 10% and which appear to be drift waves. The dependence of amplitude on radius and magnetic field and the dependence of frequency on magnetic field and ion mass indicate that these low-frequency oscillations are drift waves. We have observed that the frequency of these oscillations is always exactly equal to the frequency separation between the satellites and central peak for the driven high-frequency waves. These data indicate a strong nonlinear interaction between the driven waves propagating near the lower hybrid resonance and the drift waves which are always present in the plasma column. Furthermore, as the amplitude of the high-frequency waves increases, the low-frequency oscillation amplitude is affected and usually decreased. It is possible that this effect may be caused by a change in the plasma equilibrium induced by the driven oscillations rather than dynamic stabilization. However, the relatively intense satellites indicate a strong interaction between the low-frequency and high-frequency waves that could be of considerable interest to those workers concerned with dynamic or feedback stabilization.

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Ion Heating in High–Mach-Number, Oblique, Collisionless Shock Waves

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A mechanism for strong ion heating in oblique, collisionless shock waves is found in numerical-simulation experiments and identified with an essentially electrostatic two-ion-beam instability excited nonlinearly by the potential oscillations accompanying the whistler precursor.

In the theory of collisionless shock waves in a magnetized plasma two regimes are conveniently distinguished: (a) the resistive regime, valid for low Mach numbers, $M_A \lesssim 3$, where the main dissipation process is electron heating by anomalous resistivity; and (b) the viscous regime, valid for higher Mach numbers, where anomalous ion heating prevails. The resistive regime is now quite well understood, since the instability mechanism has been identified.[1] As it produces a microturbulence with wavelength $\lambda \sim \lambda_D$ which is much smaller than typical magnetic scales, $c/\omega_{pe} - c/\omega_{pi}$, a fluid description in terms of a phenomenological resistivity is adequate.

The so-called viscous or supercritical regime is more complicated to understand, and several different ideas on how ion heating takes place have been proposed.[2-3] The case of a perpendicu-

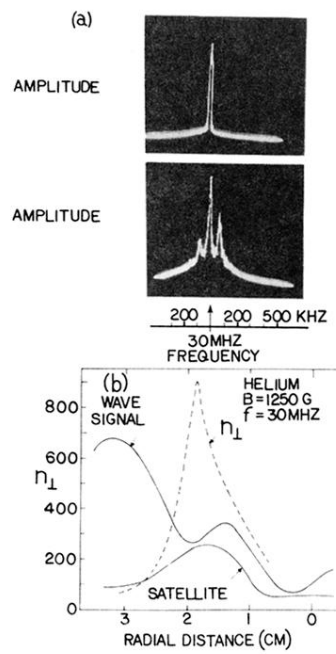

FIG. 3. (a) Frequency spectrum of the driven plasma oscillations near the plasma surface (top) and in the plasma near the region of critical density (bottom). (b) The index of refraction, the wave amplitude, and the satellite amplitude as a function of radial position.