Nonlocal plasma edge density reduction due to lower hybrid waves

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Temporal evolution of a depression of plasma edge density was observed near and away from a phased-array antenna launching lower-hybrid waves in a nearly fully ionized plasma. When equilibrium is reached, the magnitude of the depression is in agreement with ponderomotive theory.

There is a great deal of experimental and theoretical work on radio-frequency auxiliary heating of plasma. A particular advantage of some of the rf schemes for fusion application is the relatively low fraction of vacuum vessel surface area dedicated to the rf launching antenna. One such scheme is the phased waveguide array[1–3] used in lower-hybrid wave experiments. A possible drawback to this approach may be found in the relatively high-energy densities encountered when using waveguides to provide enough wave energy to heat the plasma. At these energy densities the wave pressure can be comparable to the plasma pressure, especially near the edge of the plasma. Under these circumstances, predictions[4–6] suggest that the ponderomotive force will cause a density depression to occur in the regions of high rf energy density, possibly approaching an equilibrium where the total pressure along a magnetic field line is a constant. A particularly pernicious prediction[6–8] is that reduction of the plasma density near the antenna will result in poorer coupling of the wave energy into the plasma. Nonlinear effects on coupling into lower-hybrid waves have been observed in several experiments.[6,9–11] Experimental[6,12] and theoretical[13] works have also investigated nonlinear perturbations when lower-hybrid waves converge into the so-called focal region. Experiments by Wilson[6] and Motley, Hooke, and Gwinn[14] have shown some effects on edge plasmas by lower-hybrid waves, but both experiments were limited by ionization effects to short wave pulses.

In this paper we present data showing effects of lower-hybrid waves on the edge of a nearly completely ionized plasma, with $T_i \approx T_e$. Hence, we were able to follow the wave-plasma interaction in time without concern for effects from ionization of neutrals. We found that the plasma came to an equilibrium after the rf was turned on, in which the edge density was reduced and that this edge density reduction was nonlocal, i.e., the density was depressed at the plasma edge near the antenna and also along field lines at distances far from the antenna.

The coupling of the slow lower-hybrid wave into a plasma is now reasonably well understood theoretically[1,2,15] in the linear regime. Bernabei and Fidone[15] calculate that for a slab model with linearly increasing density perpendicular to the confining magnetic field the backward wave solution near the plasma edge is given in terms of Airy functions as

$$E_{\parallel}^2 = b^2[\mathrm{Ai}^2(-\gamma^{1/3}w) + \mathrm{Bi}^2(-\gamma^{1/3}w)] \ , \qquad (1)$$

where

$$\gamma^{1/3}w = \left[\frac{(n_{\parallel}^2-1)\,\omega^2 x_c^2}{c^2}\right]^{1/3}\left[\frac{x}{x_c}-1\right] \ ,$$

b is a constant, x_c is the location of the $\omega = \omega_{\mathrm{pe}}$ layer, and x is the distance from the antenna. For our experiment, this leads to a calculated evanescent distance at the cutoff layer of 6–8 mm. Schamel and Schmidt[5] have done analytic work on the plasma response to electrostatic traveling waves and predict the density will change in the presence of the wave to

$$n = n_0 e^{-\Psi} \ , \qquad (2)$$

where

$$\Psi = e^2 E_{\parallel}^2/[2m\omega^2(T_e+T_i)] \ .$$

Decyk, Morales, and Dawson[8] have done some simulation of heating by lower-hybrid waves and have observed formation of a density cavity near the antenna.

Recently, Matsuda has found some density depression due to the perpendicular ponderomotive force as well as due to the parallel one in a $2\frac{1}{2}$-dimensional electrostatic particle simulation.[16] A spatially finite traveling wave was launched in an inhomogeneous plasma slab. Density contours obtained for several different times after wave onset indicate that there is an initial pushing of plasma down field lines out of the rf region followed by some perpendicular flow. Main simulation parameters used were $m_e/m_i = 0.01$, $\omega/\omega_{\mathrm{pe}} = 0.15$, and $\Omega_e/\omega_{\mathrm{pe}} = 3.2$.

The experiments were conducted in a single-ended Q machine[17] which provided a low-density ($\lesssim 5 \times 10^{11}$ cm^{-3} central density), low-temperature ($T_i \approx T_e \approx 0.25$ eV), nearly completely ionized potassium plasma 1.0 m long and 5 cm in diameter. The confining magnetic field was 3.5 kG for data shown.

The lower-hybrid waves were launched from a slow-wave antenna consisting of eight coaxial loops shielded from the plasma by quartz[18] with the 30-MHz signal applied to the loops controlled so that unidirectional waves of principal wavelength 12 cm were launched, and with electric fields near the antenna of ≤ 12.5 V/cm.

Plasma density was inferred from the angle of propagation, $\theta \approx \omega/\omega_{pe}$, of the resonance cone of the lower-hybrid wave with respect to $\vec{B}_0$ and from Langmuir probes. Electron temperature was inferred from a Langmuir probe. The radial wavelength and resonance cone width were measured and found to be consistent with the dispersion relation $k_{\parallel}/k_{\perp} \approx \omega/\omega_{pe}$.

Since the neutral atom population is quite small in the plasma column it was possible to follow the progression of the density depression in time without effects due to ionization limiting the wave pulse length. A steady state was reached about 700 μsec after the turn on of the lower-hybrid wave. Figure 1 shows the density depression near the plasma edge as a function of rf power. The figure shows that a depression in density occurs in the vicinity of the antenna. This depression, however, is not limited to a region near the antenna and is found to occur on the plasma surface at substantial distances (e.g., 34 cm) from the antenna (also shown in the figure).

Evidently ponderomotive effects near an rf source can affect the edge plasma in a nonlocal manner. This nonlocal adjustment of the plasma density was observed to have a leading edge which propagated down the confining field at roughly the sound speed, similar to the nonequilibrium observations of Wilson.[6] In fact, a Langmuir probe biased at −45 V placed down the field from the antenna shows an increase in ion current in time followed by a decrease in current until equilibrium is established, an effect observed by Wong and Stenzel[19] in an experiment studying enhancement of electric fields by plasma resonance.

As the density of the edge plasma changes, the lower-hybrid wave trajectory is expected to change due to the density dependence in the group velocity. The angle of propagation $\theta \approx \omega/\omega_{pe}$ should increase as the edge density falls. Figure 2 shows a radial scan of the wave energy at a distance of $z = 11.5$ cm from the center of the antenna versus time after the turn on of the rf pulse. Notice that the cone moves inward as the edge density decreases and that the cone width w, broadens, as is expected from $w \approx 12\omega/\omega_{pe}$ cm here.

As discussed earlier, the density reached in equilibrium due to ponderomotive effects is expected to go as $n \approx n_0 e^{-\Psi}$. Figure 3 shows the evolution of the edge density versus time for different electric fields applied by an antenna. Also shown are the equilibrium densities predicted by the ponderomotive theory for the region near the antenna. There is reasonable agreement between theory and experiment. We noted no change in T_e on the plasma edge (measured

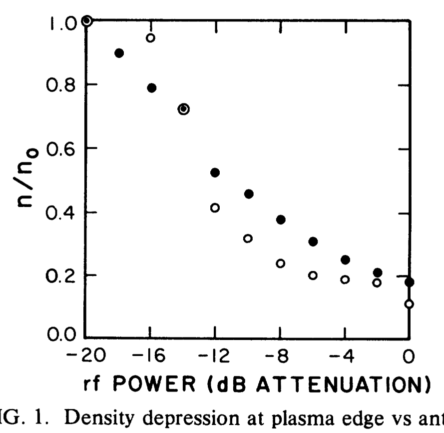

FIG. 1. Density depression at plasma edge vs antenna power. 30-MHz signal applied steady state. Closed dots determined by resonance cone trajectory near antenna. Open dots determined by Langmuir probe at $r = 2.2$ and $z = 34$ cm from center of antenna (note Langmuir probe not in resonance cone).

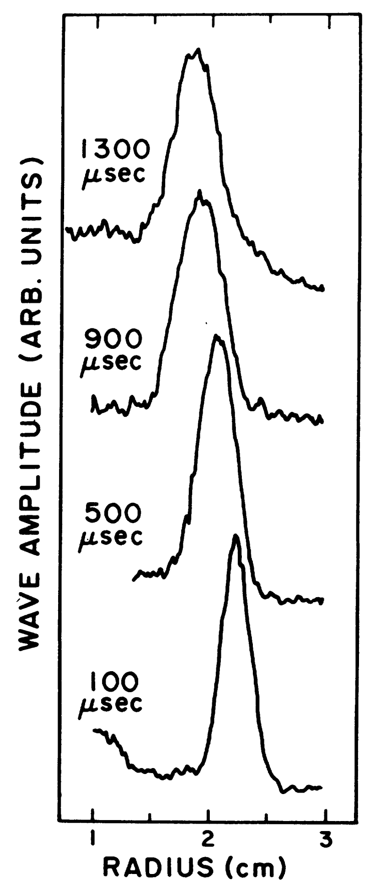

FIG. 2. Wave energy profile vs time after turn-on of rf. $\Psi \sim 0.8$.

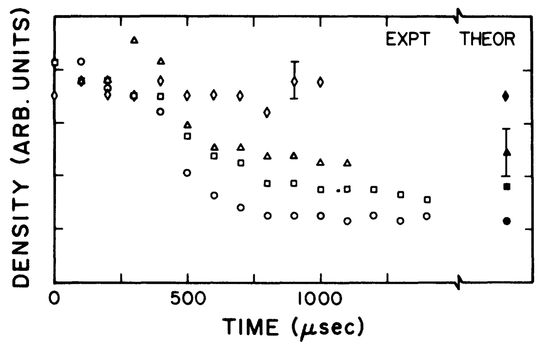

FIG. 3. Edge density vs time from turn on of rf. Open symbols are experiment, solid symbols are theory. $\Psi \approx 10^{-3}$, 0.49, 0.80, and 1.26 for ♦, ▲, ■, and ●, respectively.

downstream from the wave region), even with the higher electric fields.

In summary, we observed nonlocal density depressions at the edge of the plasma which were caused by interaction with lower-hybrid waves. These depressions could be followed in time after the start of the rf pulse and were found to come to equilibrium values consistent with predictions from ponderomotive theory. The reduction of edge density was found to alter the trajectory of the lower-hybrid waves in a manner consistent with the wave dispersion relation.

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