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Observation of Parametric Decay using CO_2 Laser Scattering in Alcator C

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Using CO_2 laser scattering parametrically excited lower hybrid waves were observed in the Alcator C tokamak. The power spectrum had a maximum at $N_{\|} \gtrsim 7$, in contrast to the pump wave spectrum which peaked near $N_{\|} \simeq 3$ ($N_{\|}$ is the index of refraction parallel to the magnetic field). Ion tail formation near the plasma edge correlated well with the occurrence of parametric decay. The consequence of these phenomena on wave propagation into the plasma interior is discussed.

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Parametric instabilities have been observed on various tokamaks during lower hybrid heating and current drive experiments at high plasma densities such that $\omega_0/\omega_{LH}(0) \lesssim 2$, where ω_0 is the frequency of the injected wave and $\omega_{LH}(0)$ is the lower hybrid frequency evaluated at the plasma center.[1,2] Since these measurements were conducted with rf probes placed in the shadow of the limiter, parametric decay in the plasma interior could not be observed directly, and neither the wavenumber spectrum nor the spatial distribution of the decay waves could be measured. In this Letter we report the results of the first experimental measurement of the wavenumber spectrum of the parametrically excited lower hybrid wave in the interior of a tokamak plasma using CO_2 laser scattering.

The Alcator C lower hybrid experiment utilizes two 4×4 waveguide arrays (MW1 and MW2) to inject up to 1.1 MW of rf power.[3] A relative waveguide phasing of 180° was used in the present experiments. The scattering volume was located 120° from MW1 and 60° from MW2 toroidally. The frequency spectra were also monitored using several rf probes at different toroidal and poloidal locations. The scattering geometry and apparatus are the same as those described in Refs. 4 and 5. The local oscillator (LO) beam (for heterodyne detection) passed vertically through the plasma at a distance $x \equiv R - R_0$ from the plasma center along the major radius. The main laser beam was oriented at a small angle to the LO beam and both beams were focused inside the plasma. In this configuration wavenumbers in the range $80 \leq k \leq 240$ cm^{-1} with orientations along the major radius could be studied. The laser beam waist radius at the focal point was 0.1 cm which gives a horizontal spatial resolution of ± 0.1 cm and a wavenumber resolution of ± 20 cm^{-1}. The vertical spatial resolution varies inversely with k and it is ± 4 cm at $k = 200$ cm^{-1}. The scattered signal was analyzed using a 16-channel filter bank for the pump wave and an 8-channel filter bank for the first ion-cyclotron harmonic lower-sideband wave (or simply, the decay wave) which, according to rf probe measurements, is almost always the dominant peak in the Alcator C experiments.[2] Higher harmonic sidebands were not studied with scattering.

By changing the scattering angle $\theta_s \simeq k/k_i$, where k is the wavenumber of the lower hybrid wave ($k \simeq k_\perp \gg k_\|$) and k_i is the wavenumber of the incident CO_2 laser beam, the k spectrum of the scattered signal can be obtained from a shot-to-shot k scan. The power density spectrum was deduced from the scattered power $P_{sc}(k)$ using the procedures described in Ref. 5. The parallel index of refraction $N_\| \equiv ck_\|/\omega$ corresponding to each value of k was obtained through the dispersion relation using the density at the midplane of the torus. We define this experimentally deduced $N_\|$ to be $N_\|^*$. $N_\|^*$ gives a lower bound on the true value of $N_\|$.

The experimentally deduced power density spectra $P(N_\|^*)$ for the pump wave and the decay wave obtained at $x = 12$ cm ($x/a \simeq 3/4$ where $a = 16.5$ cm is the limiter radius) are shown in Fig. 1. These data were obtained from three separate k scans in different ranges of k covering the range $80 \leq k \leq 240\ \mathrm{cm}^{-1}$. It can be seen that the decay wave power is concentrated at higher values of $N_\|^*$ ($N_\|^* \simeq 6$–8) than the pump wave which is peaked at $N_\|^* \simeq 2.6$ (which corresponds to $N_\| \simeq 3$).[4] The total frequency- and wavenumber-integrated power in the decay wave is at most 3% of the pump wave for this particular case, assuming that the $\vec{k}_\perp$ distributions of both the pump wave and the decay wave are isotropic in the perpendicular plane. This would be an under-estimate of the total decay wave power if $\vec{k}_\perp$ of the decay wave were oriented predominantly azimuthally rather than radially, or if more power were contained in higher ion-cyclotron harmonic sidebands which were not measured by scattering in the present experiments. For example, rf probe data indicate that the frequency-integrated decay wave power rises to $\simeq 30\%$ of the pump wave power at high densities $[\omega_0/\omega_{LH}(0) \lesssim 2]$.[2] At these densities *both* the decay wave and the pump wave power decrease rapidly with density, possibly indicating increased scattering[6] from the observed edge turbulence[7] and/or increased collisional damping near the plasma edge.[8] In a deuterium plasma, $B = 8$ T, $I_p = 380$ kA, $P_{\rm rf} = 300$ kW, at $x = +14$ cm, and $k = 140$ cm^{-1}, the decay wave has been observed by scattering only within a density band $1.9 \lesssim \bar{n}_e$ $(10^{14}$ cm$^{-3}) \lesssim 2.5$. The pump wave also becomes unobservable at densities $\bar{n}_e \gtrsim 2.5 \times 10^{14}$ cm^{-3}.

The dependences of the scattered powers from the pump and the decay waves on injected rf power are shown in Fig. 2. The decay wave is observed above a threshold rf power of $P_{\rm rf} \simeq 100$ kW for this particular case. Since the pump wave varies linearly with rf power, we conclude that for the present parameters pump depletion has not occurred.

In the present experiments the scattering volumes were located at $x = 0$, +5, +12 cm. A vertical scan at $x = 0$ cm was also carried out. The largest scattered pump and decay wave signals were observed at $x = +12$ cm, and particularly strong scattered signals were observed when the lower hybrid waves were injected from the MW2 array. Furthermore, no significant decay wave signals were detected at vertical positions $y = \pm 12$ cm at $x = 0$ cm, which correspond to the same minor radial positions as $x = +12$ cm and $y = 0$ cm. (At $y = \pm 12$ cm and $x = 0$ cm scattering is sensitive to waves with $k_\theta \gg k_r$, whereas at $x = +12$ cm and $y = 0$ cm it is sensitive to waves with $k_r \gg k_\theta$, where k_θ and k_r are the poloidal and radial components of $\vec{k}_\perp$.) In addition, both the probe and the scattering data show that the decay wave is down-shifted from the pump wave by less than the central ion-cyclotron frequency, but slightly more than the ion-cyclotron frequency at the outside edge (i.e., the larger major radius side) of the torus.[2] These observations suggest that the decay wave originated from the outside edge region, and propagated into the plasma.

Correlation between parametric decay and ion tail formation was studied using rf probes (the charge exchange data were not available when parametric sidebands were being studied with CO_2 scattering). Stronger ion tails were observed in hydrogen than in deuterium plasmas. The ion tails were observed only above the sharp density threshold of $\bar{n}_e \simeq 1.5 \times 10^{14}$ cm^{-3} in hydrogen [corresponding to $\omega_0/\omega_{LH}(0) = 1.75$ and $\omega_0/\omega_{LH}(a) = 2.9$], and $\bar{n}_e \simeq 2.0 \times 10^{14}$ cm^{-3} in deuterium [$\omega_0/\omega_{LH}(0) = 2.2$ and $\omega_0/\omega_{LH}(a) = 3.6$], both at $B = 9$ T.[9] Here, typical experimental values of $n_e(0)/\bar{n}_e = 1.3$ and $n_e(0)/n_e(a) = 3$ have been used. These density thresholds correlated well with the onset of strong parametric decay observed by rf probes. Stronger ion tails were observed by charge exchange (located at the CO_2 scattering port) when the waves were injected from MW2,[9] which is consistent with the CO_2 scattering data discussed earlier. The absence of neutron rate enhancement in the case of deuterium plasmas rules out the possibility that the ion tails originated from the plasma center.

Using the scattering data at $x/a \simeq 3/4$, namely $N_{\|2} \lesssim 8$ ($k_{\perp 2} \lesssim 190$ cm^{-1}) at the sideband (designated by subscript 2), we get $\omega_2/k_{\perp 2}v_{ti} \gtrsim 10$ and $\omega_2/k_{\|2}v_{te} \gtrsim 4$ where $v_{te,i} \equiv (2T_{e,i}/m_{e,i})^{1/2}$ and $T_e \simeq T_i \simeq 250$ eV were used. Therefore, the ion tail is not expected to be created by the lower-sideband wave. However, the low-frequency ion-cyclotron quasimode (designated by subscript 1) is heavily damped by ions since $(\omega_1 - \omega_{ci})/k_{\|1}v_{ti} < 1$, $k_{\perp 1}\rho_i \equiv k_{\perp 1}v_{ti}/\sqrt{2}\omega_{ci} \simeq 6$, and $\omega_1/k_{\|1}v_{te} \ll 1$. Higher ion-cyclotron harmonic quasimodes which correspond to $\omega_1/k_{\|1}v_{te} \simeq O(1)$ (nonresonant quasimodes[10]) are damped by both ions and electrons. Once the ion tail is formed and becomes sufficiently energetic, in principle the tail ions could absorb the lower-sideband waves. Alternatively, the sideband waves could be absorbed by electron Landau damping. Thus, the pump wave could deposit its energy near the plasma periphery through the parametric decay process. However, so far a nonlinear dependence of the pump wave power on the injected rf power has not been observed by CO_2 laser scattering (see Fig. 2).

The parametric dispersion relation derived by Porkolab,[10] was solved numerically for the present parameters. The growth rate maximizes for $\omega_1/k_{\|1}v_{te} \simeq 0.35 \quad 0.4$ when $k_{\perp 1}$ (and hence, ω_1) is varied, and it maximizes for $\omega_2/k_{\|2}v_{te} \simeq 4$ when $k_{\|1}$ (and hence, $k_{\|2}$) is varied[2] (electron Landau damping becomes appreciable for higher values of $k_{\|2}$). In Fig. 3 we show the homogeneous plasma growth rate γ (maximized with respect to $k_{\perp 1}$) and the frequency ω_1 of the quasimode (corresponding to maximum γ) as functions of radial position for the experimental situation of Fig. 1. The local pump electric field was calculated using the WKB theory assuming resonance cone propagation near the waveguide array. The sideband waves observed by CO_2 scattering probably originated near $r/a \simeq 1$ where the growth rate is largest, and subsequently propagated to the scattering volume: The fall-off of the scattered signal above $N_{\|}^* \gtrsim 8$ (Fig. 1) is probably due to the fact that waves with higher $N_{\|}$ would be damped by electron Landau damping before they can reach the scattering volume where the local temperature is $T_e \simeq 250$ eV.

The theoretically predicted homogeneous plasma threshold rf power (ignoring convective losses) at $r = 16.5$ cm is $P_{\rm rf} = 1.2$ kW. For the experimental parameters the convective threshold due to the finite width of the pump wave resonance cone[11,12] would require $\gamma/\omega_{ci} \simeq 6$ (where γ is the homogeneous growth rate). This would correspond to a threshold rf power greater than 1 MW.[2] For the experimental threshold rf power level of $P_{\rm rf} \simeq 100$ kW, $\gamma/\omega_{ci} \lesssim 1$. Therefore, in order to explain the experimental threshold a spatial spreading of the pump wave must be invoked so that the convective losses are reduced.[2] Such a spreading is expected, for example, due to scattering from low-frequency density fluctuations near the plasma edge.

In summary, the wavenumber spectrum of the parametrically excited lower-sideband waves has been measured using CO_2 laser scattering. The $N_{\parallel}^{*}$ spectrum peaked around $N_{\parallel}^{*} \simeq 7$ at $x/a \simeq 3/4$ which is consistent with the theoretical predictions. Ion tail formation near the plasma edge correlated well with the excitation of parametric instabilities and is believed to be due to ion-cyclotron damping of the low-frequency quasimodes. Since the pump wave may be absorbed near the plasma edge through the parametric decay process, suppression of parametric instabilities may be essential in achieving efficient heating and/or current drive at high plasma densities such that $\omega_0/\omega_{LH}(0) \lesssim 2$. A suppression of parametric instabilities may be achieved by raising the edge electron temperature[13] in which case the growth rates are reduced.[11] Future experiments in H-mode diverted discharges[14] would be particularly interesting. Alternatively, a reduction in low-frequency fluctuation level near the plasma periphery, if feasible, could reintroduce resonance cone propagation which would significantly raise the threshold power level for parametric decay.

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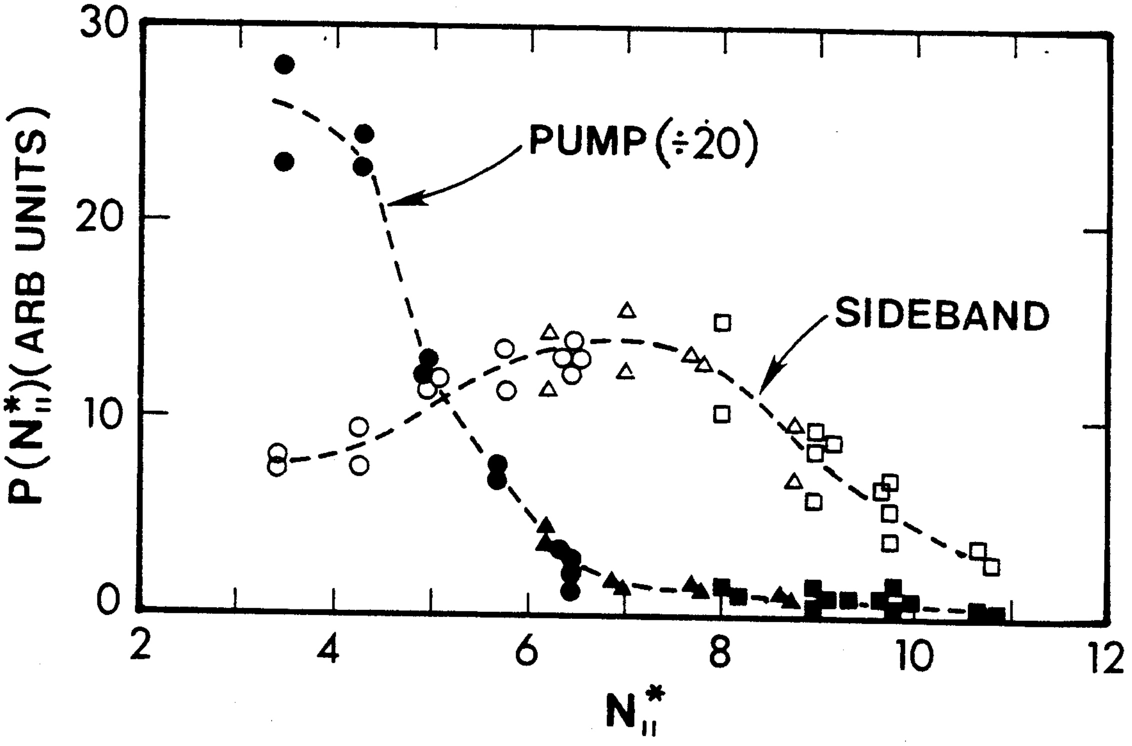
Figure Captions

Fig. 1. The $N_{\parallel}^{*}$ spectra of the pump wave (scaled down by a factor of 20) and the first ion-cyclotron harmonic sideband wave. Deuterium plasma, $B = 8$ T, $320 \leq I_p(\mathrm{kA}) \leq 360$, $1.8 \leq \bar{n}_e$ $(10^{14}$ cm$^{-3}) \leq 2.4$, $230 \leq P_{\mathrm{rf}}(\mathrm{kW}) \leq 260$, and $x = 12$ cm. Different symbols indicate data obtained from three different k scans. $N_{\parallel}^{*}$ is defined in the text.

Fig. 2. Scattered powers from the pump and the decay waves vs. injected rf power. Deuterium plasma, $B = 8$ T, $I_p = 335$ kA, $\bar{n}_e = 2.1 \times 10^{14}$ cm^{-3}, $x = 12$ cm, and $k = 150$ cm^{-1}.

Fig. 3. The maximum growth rate γ and the frequency ω_1 of the quasimode as a function of $x \equiv R - R_0$ for the experimental situation of Fig. 1. Deuterium plasma, $B = 8$ T, $\bar{n}_e = 2.1 \times 10^{14}$ cm^{-3}, $T_{e0} = 1.5$ keV, $T_e/T_i = 1$, $P_{\mathrm{rf}} = 100$ kW, $ck_{\parallel 0}/\omega_0 = 3$, $ck_{\parallel 1}/\omega_0 = 10$, and $ck_{\parallel 2}/\omega_0 = 7$.



30
20
10
0
2
4
6
8
10
12
$P(N_{\parallel}^{*})$ (ARB UNITS)
$N_{\parallel}^{*}$
PUMP (÷20)
SIDEBAND

Fig. 1

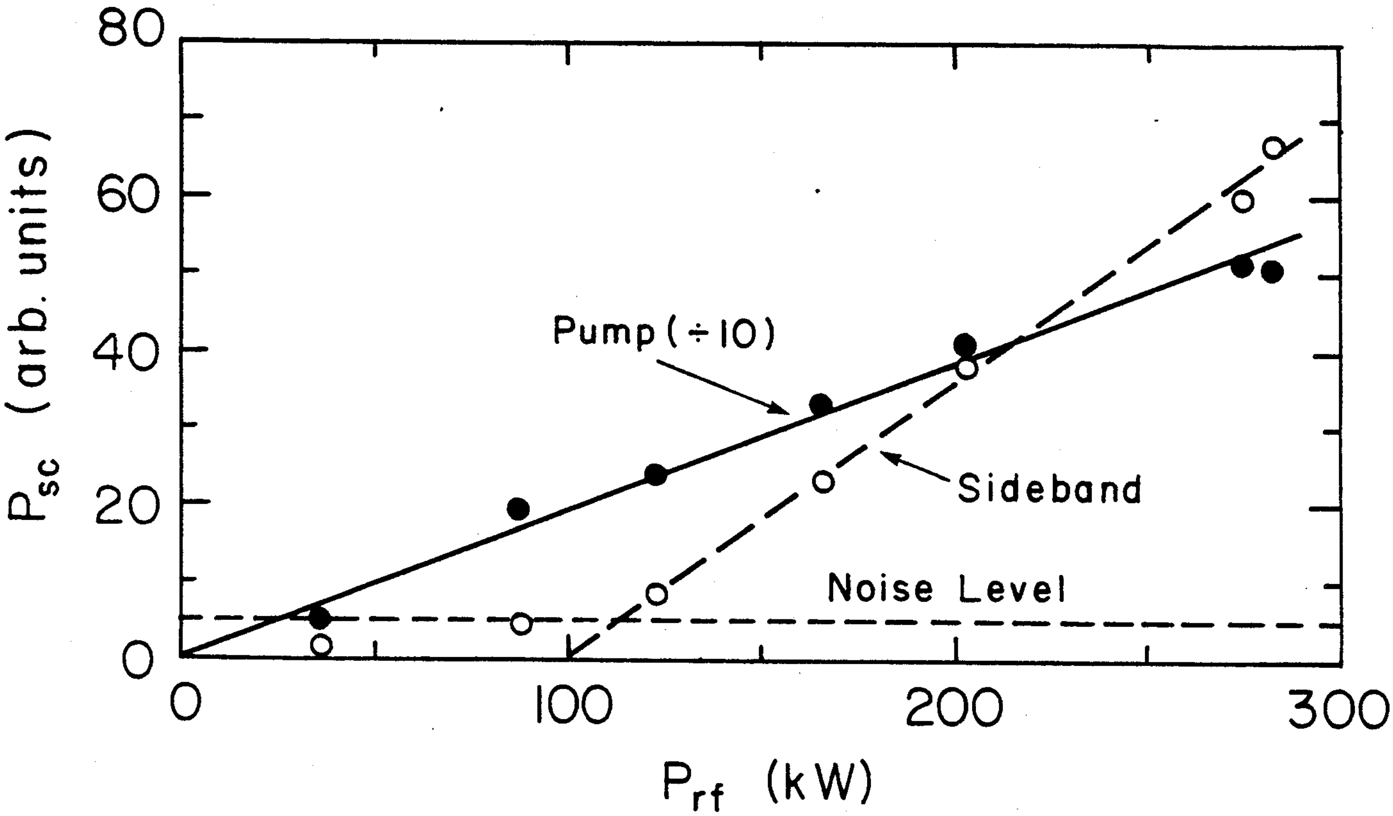

80
60
40
20
0
P_{sc} (arb. units)
0
100
200
300
P_{rf} (kW)
Pump (÷10)
Sideband
Noise Level

Fig. 2

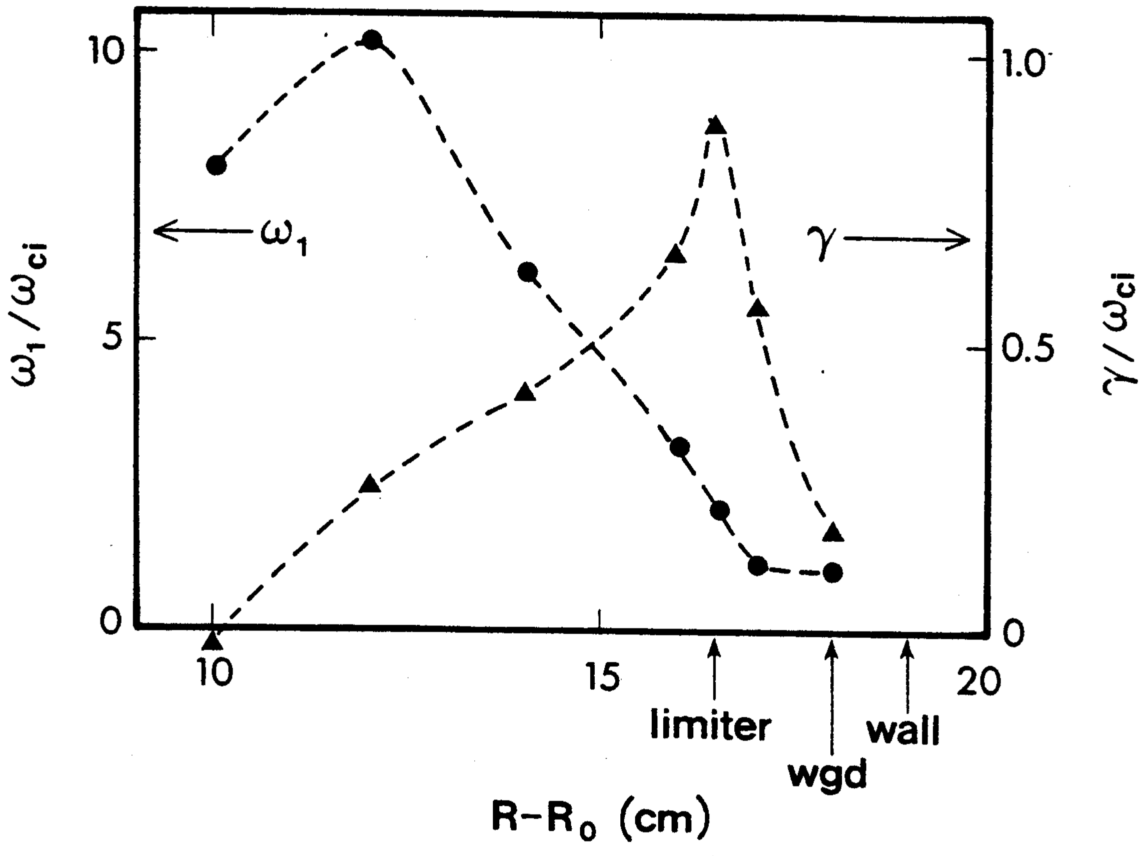


Fig. 3