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## IN THE ALCATOR C TOKAMAK

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# Spectrum and Propagation of Lower Hybrid Waves in the Alcator C Tokamak

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Waveguide-launched lower hybrid waves are studied using $CO_2$ laser scattering techniques. The $N_\parallel$ spectra of the waves near the plasma edge ($N_\parallel$ is the index of refraction parallel to the magnetic field) are similar to theoretical predictions of the launched spectrum and vary with waveguide phasing. However, the observed $N_\parallel$ spectra farther into the plasma are dominated by lower $N_\parallel$ components and are much less dependent on phasing. An explanation of these results is presented.

It has now been established that lower hybrid waves can be used to heat and drive currents in tokamak plasmas.[1,2] However, the heating and current drive depend in a sensitive way on the spectrum of wavelengths of the lower hybrid waves in the plasma. For example, current drive can be observed even when the launched spectrum is dominated by wavelength components which are too long to couple efficiently to the electrons by Landau damping.[1 2]

In this Letter, we report measurements of the spectrum of lower hybrid waves launched at a frequency of 4.6 GHz by two four-waveguide arrays in the Alcator C tokamak.[3] The relative phasing between the waveguides in each array is adjustable and this allows us to vary the $N_{\parallel}$ spectrum of the launched waves (where $N_{\parallel}$ is the index of refraction of the waves parallel to the magnetic field). The dependence of the measured spectra on waveguide phasing is studied in detail. Our measurements indicate that the wavelength and frequency spectra of the waves in the plasma are determined by the linear spectrum of waves launched by the antenna, modified by scattering from the low-frequency density fluctuations[4,5] and by the combined effects of the sheared magnetic field and toroidal geometry.[6]

Plasmas were studied in the range of line-average plasma densities $\overline{n}_e$ from 0.3 to $3 \times 10^{14}$ cm$^{-3}$ at magnetic fields $B$ from 8 to 11 T for plasma currents 200 to 450 kA. The lower hybrid waves were studied using $CO_2$ laser scattering and heterodyne detection.[4,7] The scattering angle $\theta_s$ determines the particular wavelength $\lambda_{\perp}$ (or wavevector $k_{\perp} = 2\pi/\lambda_{\perp}$) of the lower hybrid wave perpendicular to the magnetic field. To change $\theta_s$ while maintaining constant detection sensitivity, only the main beam was shifted between plasma shots. The scattered light is detected with a Ge:Cu photoconductor designed specifically for use at 4.6 GHz,[8] and the frequency spectra are measured using a parallel, 16-channel filter bank.

Scattered $CO_2$ laser radiation is collected from a portion of a vertical chord 2

mm in diameter located at positions $-0.1 \leq x/a \leq +0.9$, where $x$ is the distance at the midplane between the chord and the plasma center and $a$ is the limiter radius. This chord is $120°$ from one array (MW1) and $60°$ from the other array (MW2). The $CO_2$ laser scattering measures only a small fraction ($\lesssim 10^{-3}$) of $k_\perp$ space where the waves have $k_\perp$ oriented nearly perpendicular to the vertical chord.[7] The vertical spatial resolution along the chord was measured to be $\pm 10$ cm FWHM at $k_\perp = 80$ cm$^{-1}$ and varied inversely with wavenumber. The $k_\perp$ resolution was roughly $\pm 20$ cm$^{-1}$ for $k_\perp \geq 80$ cm$^{-1}$ and $\pm 8$ cm$^{-1}$ for $k_\perp \leq 80$ cm$^{-1}$.

The scattered power was observed to be linear with rf power as expected[5] for linear excitation of lower hybrid waves. This behavior is observed for either waveguide array operated separately for net rf powers into the torus ranging from 10 to 500 kW per array. Even at densities $\bar{n}_e \gtrsim 2 \times 10^{14}$ cm$^{-3}$ where parametric decay has been observed directly with $CO_2$ laser scattering, the pump wave power varied linearly with rf power.[9]

At low plasma densities $\bar{n}_e \lesssim 0.6 \times 10^{14}$ cm$^{-3}$ the observed signals varied significantly in time during the rf pulse as might be expected if the waves were confined to resonance cones. At higher plasma densities $\bar{n}_e \gtrsim 0.6 \times 10^{14}$ cm$^{-3}$ the scattered signals were observed to be constant ($\pm 10\%$) throughout the rf pulse. The $N_\parallel$ and frequency spectra will be described in detail for the latter case. The constant nature of the signal throughout the rf pulse suggests that the resonance cones are spread out both in real space (so that there are always waves in the scattering volume) and in $k_\perp$ space (to satisfy $\vec{k}$ matching), as would be expected from the scattering of the lower hybrid waves by low-frequency density fluctuations.[4-6,10]

In general, the scattered power observed at $x/a = 0.7$ is larger from MW2 (closer array) than from MW1 by an order of magnitude. At $x/a = 0.3$ the signals from MW1 and MW2 are comparable to the signals from MW1 at $x/a = 0.7$. At

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densities $\bar{n}_e \gtrsim 1.5 \times 10^{14}$ cm$^{-3}$ the scattered signal decreases and disappears first at small $x/a$ and then at larger $x/a$. The signal disappears at $x/a = 0.7$ for $\bar{n}_e \gtrsim 2.5 \times 10^{14}$ cm$^{-3}$.

The $N_\parallel$ spectrum of the lower hybrid waves is determined from the scattered power as a function of $k_\perp$ using the local dispersion relation to relate $k_\perp$ to $N_\parallel$ with the assumptions described in Ref. 4. For an initial analysis of the data the plasma density was assumed to be that at the midplane (i.e., $r/a = x/a$). We denote the $N_\parallel$ defined in this manner to be $N_\parallel^*$. We expect $N_\parallel^*$ to be lower than the true $N_\parallel$ of waves within the scattering volume because in general the waves are not at the midplane (i.e., they could be in a lower density region). Numerical calculations (discussed later) indicate that for the data presented the average $N_\parallel$ of waves coupling to the laser is typically within 0.3 of $N_\parallel^*$. Shown in Fig. 1 are the power spectra $P(N_\parallel^*)$ measured with the scattering volume located at $x/a = 0.7$ for adjacent waveguides phased $\pi$ and $\pi/2$ out of phase. Predictions of the spectra launched at the plasma edge (where $N_\parallel = N_\parallel^*$) by a four-waveguide array are also shown.[11] There is qualitative agreement between the theory and the measured spectra. In particular, changing the waveguide phasing produces a marked change in the spectra, and the $\pi$ phased data contain more high $N_\parallel$ components.

Shown in Fig. 2 are data for $N_\parallel^* \gtrsim 2.1$ which were taken with the scattering volume located at $x/a = 0.3$. The spectra observed with the two different waveguide phasings are similar. A vertical scan of the scattering volume at this location for $k_\perp = 80$ cm$^{-1}$ and $\bar{n}_e = 1.5 \times 10^{14}$ cm$^{-3}$ ($N_\parallel^* \simeq 3.5$) verified that the signal originates from near the midplane and not the plasma edge. However, for lower values of $k_\perp$, where measurements of this type could not be done, our numerical modeling indicates that this localization may not be true.

Frequency spectra of the scattered signals indicate that the lower hybrid waves

have a frequency width $\Delta\omega$ of up to 6MHz (FW to $1/e$ power point). This width increases monotonically with both $\bar{n}_e$ and $k_\perp$. A small frequency down-shift was also observed, particularly at high density, but in all cases this shift was less than 20% of $\Delta\omega$.

The lower hybrid waves are expected to have a frequency width due to scattering from the large-amplitude low-frequency density fluctuations present near the edge of plasmas in Alcator C. Using the measured mean frequency, correlation length, and amplitude of these fluctuations,[4] the theory predicts both a magnitude and $k_\perp$ dependence of $\Delta\omega$ in good agreement with our measurements.[5,10] This model can then give a *quantitative* measure of the scattering of the lower hybrid waves. In terms of the thickness $L$ of the edge turbulence ($L \simeq 1$ cm)[5] and the distance $l_{90°}$ in which a lower hybrid wave will be scattered by 90°, the model indicates values of $L/l_{90°}$ ranging from 0.5 at low density and high $N_\parallel$ to values $\gtrsim 4$ at high density and lower $N_\parallel$. This level of density fluctuation scattering can then significantly affect the propagation and damping of the lower hybrid waves. The scattering can give the waves poloidal wavevector components $k_\theta$ of the order of $k_\perp$. As these waves propagate radially inward through the sheared magnetic field, these values of $k_\theta$ produce significant changes in $N_\parallel$ (e.g., $1 \lesssim \Delta N_\parallel \lesssim 3$).[5,6,10] Waves with up-shifted values of $N_\parallel \gtrsim 5$ can then electron Landau damp rapidly in the central region of the plasma.

Numerical calculations have been carried out for the propagation of lower hybrid waves using a toroidal ray tracing code and a Monte-Carlo technique[6] to model the scattering from the experimentally measured density fluctuations.[5] Wave absorption due to linear electron and ion Landau damping and due to Coulomb collisions are included. The power spectra inside the plasma are simulated by launching a Brambilla power spectrum[11] at the plasma edge. Each component was

weighted to a power appropriate to the waveguide phasing under consideration. The lower hybrid wave power detected by the laser was then simulated by accumulating all rays whose $k_\perp$'s are within the experimental resolution of the particular $k_\perp$ under consideration and whose $\vec{k}$ vectors are oriented nearly perpendicular to the laser beam at the appropriate chord location and toroidal angle. As expected,[5] the inclusion of density fluctuation scattering in the simulation model is essential in order that the wave be able to couple to the laser beam. The scattering tends to make $\vec{k}_\perp$ isotropic, thus enhancing the probability of the wavevector $\vec{k}$ being perpendicular to the beam.

Simulations of the power spectra at $x/a = 0.7$ are in good agreement with the data shown in Fig. 1(a) for $\pi$ phasing and are in fair agreement with the data shown in Fig. 1(b) for $\pi/2$ phasing. These calculations indicate, in agreement with the data, that the spectra observed near $x/a = 0.7$ originate predominantly from MW2 having come the short way around the torus. The simulated power spectra show that the average values of $N_\parallel$ for waves coupling to the laser beam at fixed $k_\perp$ are higher than the values $N_\parallel^*$ shown in Figs. 1(a) and (b) by $\Delta N_\parallel \simeq 0.3$. For example, the peak at $N_\parallel^* \simeq 2.6$ shown in the data for $\pi$ phasing corresponds to a true $N_\parallel$ of 2.9. This difference is due to the fact that the simulated rays which are observed by the laser lie near $r/a = 0.8$ rather than $r/a = 0.7$ used to determine values of $N_\parallel^*$. At fixed $k_\perp$ the lower density in this region means that rays with higher $N_\parallel$ would be observed. Thus, the numerical results indicate that the data in Fig. 1(a) is actually quite close to the initial Brambilla spectrum. However, the simulations do not account for the cutoff at $N_\parallel^* \lesssim 2.2$ which appears in the $\pi/2$ data [Fig. 1(b)].

The Monte-Carlo simulations of the power spectra at $x/a = 0.3$ are in qualitative agreement with the data shown in Fig. 2 for both waveguide phasings. The

simulation values of $N_\parallel$ are generally greater than $N_\parallel^*$ with the difference being less than 0.4 for $N_\parallel^* \lesssim 2.4$ and are negligible for $N_\parallel^* > 2.4$. We find that waves with initial $N_\parallel > 2.75$ have a high probability of being up-shifted in $N_\parallel$ and then damped rapidly as discussed above. The results also indicate that waves with initial values of $N_\parallel \lesssim 2.75$ are not up-shifted enough in $N_\parallel$ to Landau damp. Instead, these waves can make several toroidal transits, enhancing the probability of the wave coupling to the laser. These multiple passes can then contribute to an increased signal.[5,7] Thus waves with $N_\parallel < 2.75$ dominate the observed spectra. Another result of the simulations is that the power spectrum for $\pi$ phasing may exhibit a peak near the lowest observed $N_\parallel$, suggesting that although the observed spectra at $x/a = 0.3$ and $N_\parallel^* \gtrsim 2.1$ are similar for both $\pi$ and $\pi/2$ phasing, they may be quite different at $N_\parallel^* < 2.1$.

The decrease of the observed signal at high densities $\bar{n}_e \gtrsim 2.5 \times 10^{14}$ cm$^{-3}$ at both $x/a = 0.3$ and $x/a = 0.7$ is due in part to the increased collisional absorption near the plasma edge.[12] In addition, for the $x/a = 0.3$ data, density fluctuation scattering produces $N_\parallel$ up-shifts which decrease the wave amplitude due to electron Landau damping. However, at present it is not clear that these effects can explain the disappearance of the signal.

In summary, we have measured the frequency and wavenumber spectra of lower hybrid waves in a tokamak plasma under conditions in which these spectra depend on the relative phasing of the exciting waveguides. These data allow a quantitative comparison with theories for the propagation of the waves in tokamak plasmas. A preliminary result of this comparison is that the scattering of the waves by density fluctuations and the subsequent propagation through the sheared magnetic field is important in determining the $N_\parallel$ spectra.

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## Figure Captions

Fig. 1. The power spectra $P(N_{\parallel}^*)$ (where $N_{\parallel}^*$ is deduced from $k_{\perp}$ and using the midplane density) of the lower hybrid waves measured with the laser beam at $x/a = 0.7$: (a) adjacent waveguides phased $\Delta\phi = \pi$ and (b) $\Delta\phi = \pi/2$. For these data $N_{\parallel}^*$ is lower than the average $N_{\parallel}$ by about 0.3. The solid curves are theoretical predictions for the power spectra launched at the plasma edge[11] (where $N_{\parallel}^* = N_{\parallel}$) and are normalized to match the data in (a). These data are for deuterium plasma at $B = 8$ T and $\bar{n}_e = 1.5 \times 10^{14}$ cm$^{-3}$ (i.e., electron heating regime in Alcator C).

Fig. 2. $P(N_{\parallel}^*)$ measured with the laser beam at $x/a = 0.3$ for both $\Delta\phi = \pi$ (triangles) and $\pi/2$ (solid circles). The plasma conditions are as in Fig. 1, except $\bar{n}_e = 1.3 \times 10^{14}$ cm$^{-3}$. Here $N_{\parallel}^*$ differs significantly from the average $N_{\parallel}$ only for $N_{\parallel}^* < 2.4$, where $(N_{\parallel} - N_{\parallel}^*) \lesssim 0.4$.
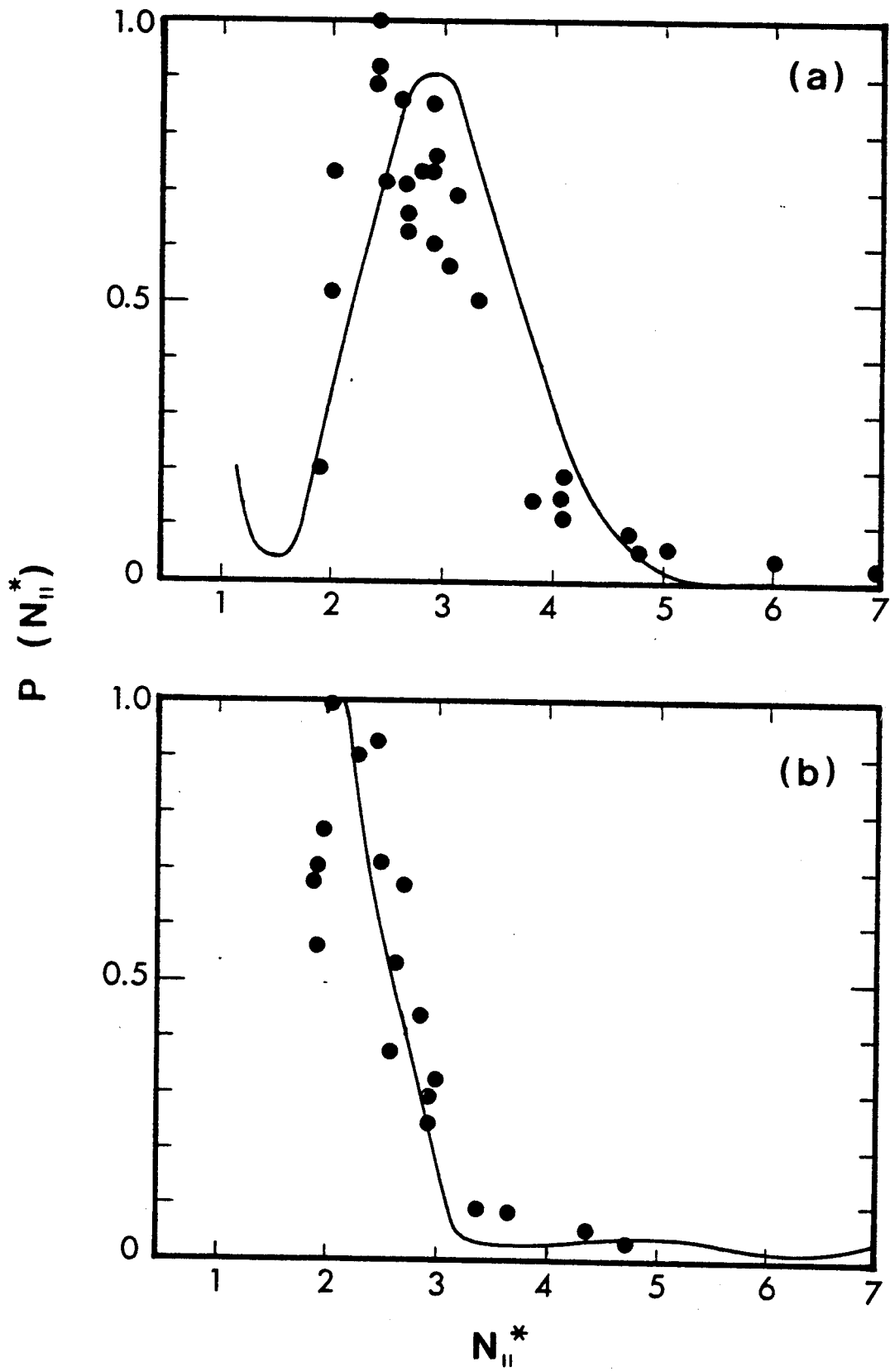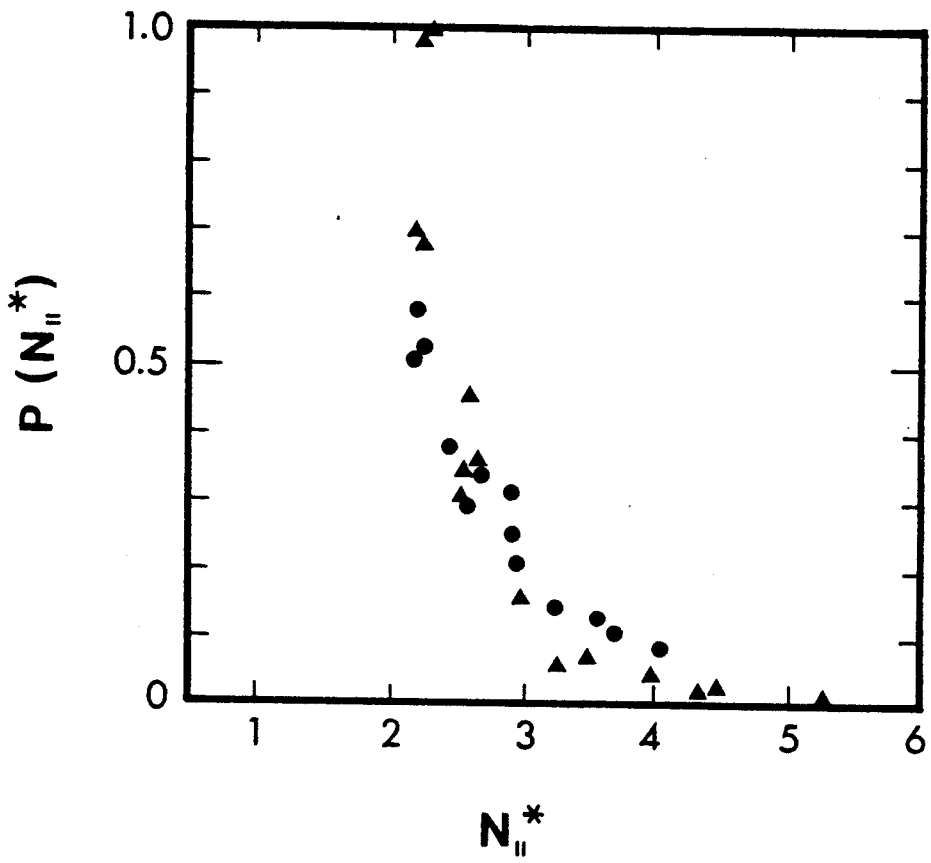
FIGURE 1

FIGURE 2

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