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Observation of Mode-Converted Ion Bernstein Waves in the Microtor Tokamak

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Mode-conversion processes play an important role in the radio-frequency heating of tokamak plasmas. This paper reports the first direct observation of externally driven ion Bernstein waves in a tokamak plasma. The waves are only observed in mixed-species plasmas near the ion-ion hybrid resonance layer and are interpreted as being the result of linear mode conversion of the fast magnetosonic wave.

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It is generally believed that Ohmic heating alone is insufficient to produce thermonuclear ignition in tokamak plasmas and that, therefore, auxiliary heating is required. Recent experiments have demonstrated the great promise of rf heating in the ion-cyclotron range of frequencies.[1,2] However, the primary thrust of this previous work has been toward plasma heating and not wave propagation and accessibility.

The present work reports the first direct, internal, nonperturbing observation in a tokamak of externally driven waves in the ion-cyclotron range of frequencies. This has been achieved with cw far-infrared laser scattering techniques.[3] A major result has been the conclusive identification of mode conversion of the fast magnetosonic wave into an ion Bernstein wave in the vicinity of the ion-ion hybrid resonance layer. This process, predicted to occur in mixed-species plasmas,[4] is thought primarily responsible for heating results obtained in the TFR[2] and DIVA[5] tokamaks. However, until this time no direct, independent experimental verification of the existence of mode-converted Bernstein waves has been achieved.

The experiments were conducted in the University of California, Los Angeles, Microtor tokamak. The device parameters are major radius, $R_0 = 30$ cm, minor radius $= 10$ cm, $B_T = 10 - 25$ kG, $I_p = 60 - 100$ kA, $n_e = 10^{13} - 3\times10^{14}$ cm^{-3}, $T_e \leqslant 600$ eV, and $T_i \leqslant 300$ eV. Electromagnetic antennas (10 MHz $\leqslant \omega/2\pi \leqslant$ 35 MHz, $P_{\mathrm{rf}} \leqslant 25$ kW) were located at toroidal reference planes of 45°, 90°, 225°, and 270°. In addition, two separate far-infrared laser scattering systems were positioned at reference positions of 135° and 315°. Through simultaneous observation of scattering signals with the two lasers and by alternation of excitation antennas, toroidal propagation effects could be studied.

The far-infrared laser scattering systems both employed homodyne detection of the radiation scattered from an optically pumped cw $^{13}\mathrm{CH_3F}$ probe laser operating at 245 GHz.[3] The output of the laser was weakly focused to a beam waist of $\simeq 2$ cm on the equatorial plane of the plasma resulting in a wave number resolution $\Delta k = \pm 1$ cm^{-1}. Variation of scattering angle allowed wave numbers k_w in the range $0 < k_w < 18$ cm^{-1} to be observed. The spatial resolution along the incident beam is dependent on the scattering angle. However, in Microtor the majority of scattering data were obtained for $\theta_s \leqslant 10°$ and were essentially chord averaged.

The scattered far-ir signal, which is shifted in frequency by the wave frequency (=10 – 35 MHz), is downconverted in a quasioptical GaAs Schottky-barrier diode mixer.[3] The scattered electric field amplitude is monitored with use of a tunable, narrowband (bandwidth 100 – 300 kHz) filter. This signal is given by

$$E_s(\theta_s, k_w) \propto \tilde{n} \exp[-\tfrac{1}{2}(k_w - 2k_0 \sin\theta_s/2)^2 a_0^2], \qquad (1)$$

where $\tilde{n}$ is the density fluctuation amplitude, k_0 is the incident far-ir laser wave number, θ_s is the scattering angle, and a_0 is the beam waist in the scattering volume.

The Gaussian term is simply the result of wave-number matching. When the scattering wave number $[k = 2k_0 \sin(\theta_s/2)]$ matches k_w this term is a maximum. If k_w changes so that a mismatch occurs, the scattered electric field falls off as a Gaussian with a $1/e$ width determined by the beam waist.

In Microtor, the toroidal magnetic field varies temporally as well as spatially. At a fixed spatial position this sweeps ω/ω_{ci} in time and therefore modifies k_w in a manner determined by the wave dispersion. This gives rise to a time-varying signal with amplitude determined by Eq. (1) and the wave properties. Typical scattering signals at several radial locations are shown in Fig. 1 for the case of a mixed-ion-species plasma (deuterium puff, hydrogen fill). The rf frequency was fixed at $\simeq 20$ MHz and the peak toroidal field at the center was 23 kG ($\omega_{\rm rf} \simeq 2\omega_{cD}$).

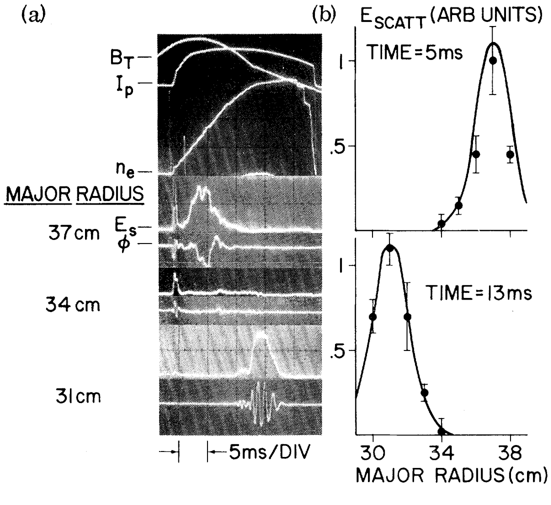

FIG. 1. (a) Typical tokamak and scattered electric field and phase signals for H/D plasma: $I_p = 50$ kA/div., $B_T = 23$ kG peak, 4.8 kG/div., $n_e \approx 4\times 10^{13}$ cm^{-3}/div., and $f_{\rm rf} \simeq 20$ MHz. (b) Radial dependence of scattered electric field for the times corresponding to the peak of the "outer" (t = 5 ms) and "inner" (t = 13 ms) modes.

The chord-averaged data indicates a quiescent region of little wave activity centered on a chord at a major radius of 34 cm ($R_0 = 30$ cm). This observed quiescent region separates two distinct regions of wave activity along chords centered at $R = 31$ and 37 cm. Experimental evidence strongly supports the interpretation that two very different waves exist in these two spatial locations. As shown below, the interior mode ($R \simeq 37$ cm) is conclusively identified as an ion Bernstein wave produced via linear mode conversion of the fast magnetosonic wave.[4] The outer mode ($R \simeq 37$ cm) has been tentatively identified as a modified slow Alfvén wave.[6]

Let us now describe the properties of the waves observed along interior chords. These waves were found *only* to exist during second-harmonic experiments in mixed-species plasmas where ion-ion hybrid resonances are present. It should be stressed that they were *not* observed in pure hydrogen or deuterium plasmas. Second, the waves were only present when normal induction excitation was adopted. By varying of the phase of the antenna excitation the usual magnetic coupling could be changed to essentially purely electrostatic excitation. In this case, virtually no wave activity was observed. This is consistent with our other observation that the presence (or absence) of Faraday shields on our dielectric-enclosed launching antennas did not significantly alter the observed phenomena. The above observations are strongly indicative of linear mode conversion of the fast magnetosonic wave to an ion Bernstein wave. In addition, it should also be noted that the amplitude of the scattered electric field was found to be rather constant (factor of 2) toroidally. This also supports the fast-wave mode-conversion interpretation since the fast wave suffers relatively little damping toroidally and should therefore excite Bernstein waves uniformly around the torus.

Further confirmation has been obtained by studying the chordal location of the observed waves as a function of the D/H concentration ratio. The results are illustrated in Fig. 2 where the scattered electric field amplitude at a fixed time (fixed B_T) is plotted versus major radius for two separate D/H-ratio plasmas. Although the absolute D/H was not known accurately, the expected trend, illustrated by the plot of the dependence

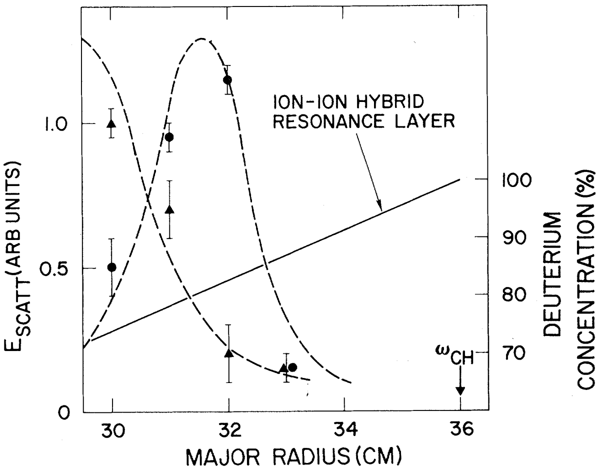

FIG. 2. Radial dependence of scattered electric field from ion Bernstein wave for two D/H concentration ratios.

of the hybrid layer position with species concentration, was observed. Smaller minority (H) concentrations resulted in the peak scattered power moving to the low-field region.

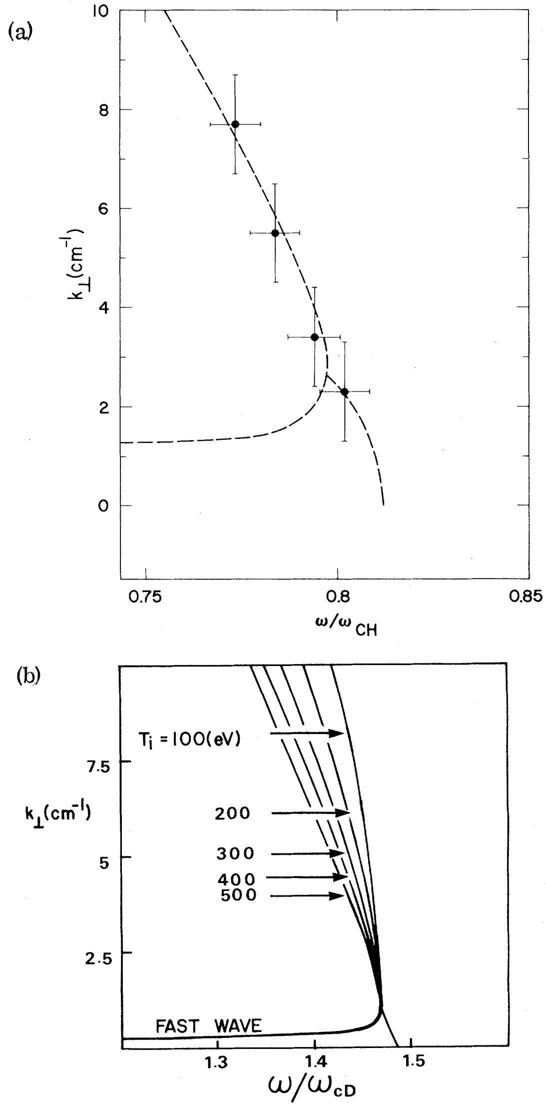

FIG. 3. (a) Experimental points and theoretical dispersion for mode-converted ion Bernstein wave in a D/H plasma. Theoretical parameters are $n_\mathrm{H}/n_\mathrm{D} = 0.5$, $n_e = 5\times10^{13}$ cm^{-3}, $T_e = 400$ eV, and $T_i = 200$ eV, and $k_\parallel = 0.05$ cm^{-1}. (b) Ion temperature variations of the mode-converted ion Bernstein wave dispersion relation ($k_\parallel = 0.05$ cm^{-1}, $n_e = 4\times10^{13}$ cm^{-3}, $T_e = 400$ eV, $B_T = 16$ kG, $f_\mathrm{rf} = 22$ MHz, $n_\mathrm{H}/n_\mathrm{D} = 1$).

A final confirmation of the identity of the interior mode is obtained by comparing the measured wave dispersion with theoretical predictions for the mode-converted Bernstein wave obtained by numerical solution of the full hot-plasma dispersion equation in the local approximation. The results are shown in Fig. 3(a). To obtain the experimental dispersion, an angular scan was performed on a shot-to-shot basis. For each angle (or k value) the time at which the peak signal occurred was obtained and by use of the known toroidal field time and space dependence the appropriate value of ω/ω_{ci} is determined. Associating the peak signal in time with the wave number determined by the Bragg condition assumes a constant wave amplitude over the k resolution of the scattering system ($\Delta k = \pm 1$ cm^{-1}). The agreement between experiment and theory is seen to be excellent. The theoretical parameters are $n_\mathrm{H}/n_\mathrm{D} = 0.5$, $n_e = 5\times10^{13}$ cm^{-3}, $T_e = 400$ eV, $T_i = 200$ eV, and $k_\parallel = 0.05$ cm^{-1}. The slope of the computed wave dispersion is primarily sensitive to T_i. This is illustrated in Fig. 3(b) where the wave dispersions for a variety of T_i are plotted. This sensitivity of wave dispersion to ion temperature may prove a useful diagnostic technique if the necessary improvements in wave launching structure are made so that the parallel wave number spectrum is narrowed. The computed wave dispersion is, however, relatively insensitive to variations in $k_\parallel$ and n_e and such a method of determining T_i clearly warrants further investigation.

Let us now turn our attention to the waves observed along the outer chord illustrated in Fig. 1. In this case, the rf frequency was $\simeq 2\omega_{c\mathrm{D}} = \omega_{c\mathrm{H}}$ and the waves were observed over a range of frequencies below the hydrogen cyclotron frequency ($0.8\omega_{c\mathrm{H}} < \omega < \omega_{c\mathrm{H}}$). However, when the rf frequency was lowered to ~10 MHz ($\simeq \omega_{c\mathrm{D}}$) waves were then observed near the deuterium cyclotron resonance ($0.8\ \omega_{c\text{D}} \leqslant \omega \leqslant \omega_{c\text{D}}$). At this launching frequency it should be noted that the ion Bernstein waves were not observed since the ion-ion hybrid resonance was not reached. It should be stressed that these waves were also observed in pure hydrogen or deuterium plasmas. Of course, in this instance, the ion-ion hybrid resonance does not exist and so again ion Bernstein waves were not observed. Numerical solution of the hot-plasma dispersion equation in the local approximation for a mixed-species plasma indicates the existence of modified slow-wave branches below each species cyclotron frequency. These branches are similar to but an extension of the kinetic Alfvén wave described by Hasegawa and Chen[7] for frequencies $\omega \ll \omega_{ci}$. The observed waves are therefore tentatively interpreted as slow Alfvén/ion-cyclotron modes modified by finite Larmor radius effects.

The computed wave dispersion for this modified slow wave is found to be highly sensitive to electron temperature, parallel wave number, and density variations. Agreement with the experimentally determined wave dispersion is reasonable. However, a detailed comparison is beyond the scope of this paper since time-varying parameters such as n_e, T_e, and B_T make such a comparison complicated.

A knowledge of the absolute value of the density fluctuation level associated with both of the observed waves is of importance. The assumption that the waves completely occupy the scattering volume results in an estimated value of $\tilde{n} = 10^{10}$ cm^{-3}. This is in substantial agreement with the value inferred from the antenna loading if one assumes complete absorption in the plasma volume occupied by the mode-converted waves. However, it should be noted that, because of the uncertainties associated with k matching and coherent phase effects, estimates obtained from the scattering data could be considerably in error. Finally, it should also be noted that for rf input powers up to 25 kW the scattered far-ir power scaled linearly with rf input power for both modes.

In summary, we have observed for the first time externally driven waves in the ion-cyclotron range of frequencies. In particular, ion Bernstein waves have been conclusively identified, localized near the ion-ion hybrid layer in mixed species plasmas. In addition, waves have been observed near and below ($0.8\omega_{ci} \leqslant \omega \leqslant \omega_{ci}$) fundamental cyclotron frequencies in both mixed- and single-species plasmas. These waves have been tentatively identified as modified slow waves similar to the kinetic Alfvén wave described by Hasegawa and Chen[7] but existing in a very different parameter regime.

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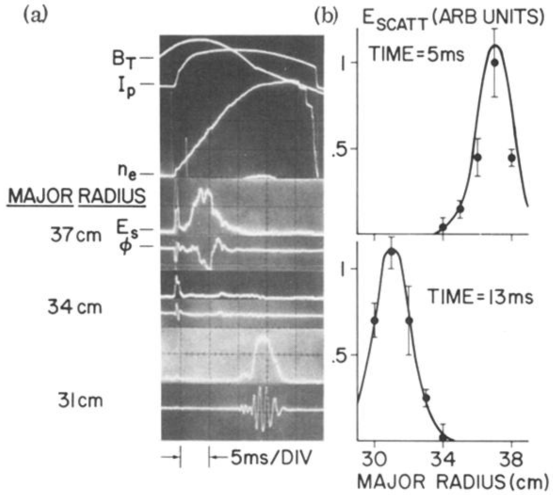

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