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OBSERVATION OF MAGNETIZED-ION THERMAL EFFECTS
ON LOWER-HYBRID WAVES

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FEBRUARY 1983

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CND-3073.

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OBSERVATION OF MAGNETIZED-ION THERMAL EFFECTS
ON LOWER-HYBRID WAVES

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Finite ion Larmor radius modification of lower-hybrid waves in the ACT-1 toroidal plasma at frequencies $\omega = 4-8\omega_{ci}$, close to the lower-hybrid resonance layer, is observed experimentally. Probe and CO_2 laser scans of the wave amplitude show interference patterns at frequencies above each ion cyclotron harmonic. Modeling with a hot-ion, electrostatic ray tracing code and Fourier reconstruction of the waveform suggests that linear mode conversion to hot plasma waves is occurring.

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Lower-hybrid waves (LHW) are of importance to ion and electron heating as well as to driving toroidal currents in tokamak fusion devices. Linear mode conversion of LHW into hot plasma waves (HPW) and then into ion Bernstein waves (IBW) as the LHW approach the lower-hybrid resonance layer from the low density side was predicted theoretically by Stix¹ in 1965, and sketched for a single parallel wavenumber $k_{\parallel}$. In 1969, Fisher and Gould² showed experimentally that LHW propagate in resonance cones when a spread in $k_{\parallel}$ is launched from an antenna. Since this time, a number of authors³⁻⁶ have suggested that resonance cones from a localized source antenna are maintained throughout the mode conversion processes. This idea has influenced experimental searches for LHW $\rightarrow$ HPW mode conversion, none of which have reported success.⁷ However, in a manner analogous to (but more complicated than) finite electron temperature causing well-known dispersion and interference effects,⁸ the inclusion of finite ion temperature in a magnetized plasma causes extensive spatial dispersion and interference structures in the wave packet of the original LHW near the LH resonance layer. As has been pointed out by Simonutti,⁹ a key signature of the mode conversion processes would be a periodicity of waveforms in the parameter $\eta = \omega/\omega_{ci}$, where ω_{ci} is the local ion cyclotron frequency, and $f = \omega/2\pi$ is the launching frequency from the antenna.

In this report, we describe the first experimental observation of finite ion Larmor radius modifications of lower-hybrid waves, characterized by ion cyclotron periodicity, in close vicinity ($1 \lesssim \omega/\omega_{th} < 2$) to the lower-hybrid layer $\omega_{lh} = \omega_{pi} (1 + \omega_{pe}^2/\omega_{ce}^2)^{-1/2}$, where ω_{pi} , ω_{pe} , and ω_{ce} are the usual definitions of the ion plasma, electron plasma, and electron cyclotron frequency, respectively. Mode conversion of the lower-hybrid wave to hot

plasma waves is required to calculate patterns observed in the data, having used experimentally determined radial electron density, ion temperature, electron temperature, toroidal magnetic field profiles, and ion concentration information as input parameters.

This experiment was performed in the Princeton Advanced Concepts Torus (ACT-1) steady-state toroidal plasma device¹⁰ at frequencies $\omega \sim 4-8 \omega_{ci}$ or $f \sim 25-50$ MHz, with $n_e \sim 2-8 \times 10^{10} \text{ cm}^{-3}$, $T_i \sim 0.5-2$ eV, $T_e \sim 0.5-3$ eV, $B_0 \sim 4.5$ kG, and parallel wavelengths launched by the antenna covering the range $\lambda_{\parallel} \sim 2-20$ cm. The antenna structure consisted of six narrow (width $\Delta x = 0.65$ cm) plates on 1.3 cm centers located on the outer major radius edge of the plasma at a midplane minor radius of $r = 6.5$ cm and protected by limiters at $r = 6$ cm. Only one of the central plates was powered (< 0.1 Watt to avoid nonlinear effects¹¹), resulting in a broad $k_{\parallel}$ -spectrum and waves launched in both directions around the torus. The filament-produced hydrogen plasma consisted of H_1^+ , H_2^+ , and H_3^+ , in the ratio $0.45:0.27:0.28 \pm 0.05$, measured by ion cyclotron wave resonance cone techniques.¹² Radial ion temperature information was obtained via second harmonic ion Bernstein wave measurements using RF probes and CO_2 laser scattering.¹³ Radial electron density profiles, measured from high frequency ($\omega \gg \omega_{lh}$) lower-hybrid resonance cone angles and Langmuir probe traces, complete the basic plasma parameters.

ACT-1 differs from older devices⁷ with regards to LHW studies in four important respects. The ion temperature is higher, so that waves with $k_{\perp} \rho_i \sim 0.5-2$, where ρ_i denotes the ion Larmor radius, are readily obtained. Long effective machine lengths are achieved (a torus) so that the wave can approach the resonance layer along weak gradients in the perpendicular (radial or x) direction with no gradients in the parallel direction. Since the plasma source is in the inner half of the torus, fast

electrons (by the nature of their vertical drifts) are effectively isolated from the observation region, and thus electron Landau damping on a superthermal tail is not a problem.¹⁴ Finally, the toroidal magnetic field (there is no poloidal field) falls off as one over the major radius, so that the wave is launched into a plasma with $\nabla_{\mathbf{x}} n \cdot \nabla_{\mathbf{x}} B > 0$, usually encountering one to two cyclotron harmonic layers before reaching the axis.

In Fig. 1, probe signals of wave amplitude versus radius, obtained using a tuned spectrum analyzer as a narrow band filter, are plotted as a function of launching frequency. The probe was 9 ports (26 ports $\sim 360^\circ$) away from the antenna toroidally. The largest feature on each trace is the resonance cone from the short way around the torus, while features closer to $r=0$ cm have come from the long way around the torus. The most interesting data are near 32-34 MHz, 40-41 MHz, and 48 MHz. Wave amplitude is seen to pile up in front of the fifth, sixth, and seventh ion cyclotron layers (denoted by diagonal lines). Interference patterns, changing dramatically for frequency differences of only 0.25 MHz, appear with cyclotron periodicity. These patterns are very sensitive to small changes in plasma parameters or magnetic field, and also appeared on wave interferometry probe traces. At $f=32$ MHz, the bump near $r=2$ cm corresponds to $f/f_{p1}=1.1$, while at $f=40.5$ MHz, the sharp feature at $r=1$ cm corresponds to $f/f_{p1}=1.2$. Finally, broadening of the main cone is visible near each harmonic layer.

When examined with CO_2 laser scattering, which selectively detects different $k_{\perp}$, similar patterns were observed. Phase velocity was consistent with a backward wave propagating into the plasma, or a forward wave propagating out of the plasma. The $k_{\perp}$ detected ranged from 25-60 cm^{-1} . Coherence problems prevented seeing $k_{\perp} > 60 \text{ cm}^{-1}$ at the low power levels required to avoid perturbing the plasma. However, to detect directly the hot

plasma wave, it can be deduced from Fig. 2(a), which shows $k_{\perp}$ versus radius at $f=41$ MHz for various $\lambda_{\parallel}$, that $k_{\perp}$ should be in the range of $50-100 \text{ cm}^{-1}$. The Bernstein wave should exist even higher, $k_{\perp} \sim 100-200 \text{ cm}^{-1}$. To explain the experimental observations, which are not consistent with LHW alone, requires that the LHW interfere with, for example, the hot plasma wave to produce the observed $k_{\perp}$. This is suggested by corresponding ray tracing results shown in Fig. 2(b), where it can be seen that mode conversion to the HPW and IBW breaks up the initial resonance cone, since the LHW + HPW conversion points for different $\lambda_{\parallel}$ are at widely differing toroidal and radial locations. Since the hot plasma wave region is defined between the two turning points (LHW+ HPW and HPW+ IBW), the latter of which depends strongly on proximity to an ion cyclotron harmonic layer, strong magnetic field dependence is expected.

In order to simulate the probe data to see if such interference patterns could in fact be generated, a computer code was written to reconstruct the radial profile of the RF electric field amplitude, $E_{\perp}(x,z)$. The antenna $k_{\parallel}$ spectrum (each component $A_{k_{\parallel}}$) is assumed to be given, and in fact has been estimated with the laser scattering system. For this two dimensional problem, 80 $k_{\parallel}$ components, centered in a Gaussian about $k_{\parallel}=0.9 \text{ cm}^{-1}$, are numerically propagated into the plasma in the WKB sense:

$$E_{k_{\parallel}}(x) = A_{k_{\parallel}} \exp\{i \int_0^x k_{\perp}(k_{\parallel}, x') dx'\} 1/|k_{\perp}(x)|^{1/2}.$$

Here $k_{\perp}$ (complex) is obtained by root-finding the hot ion electrostatic dispersion relation, given the magnetic field, plasma parameter profiles, and $k_{\parallel}$. Electromagnetic effects are unimportant, and can be ignored for ACT-1 parameters.¹⁵ At points of mode conversion, where $dx/dk_{\perp} = 0$, the WKB approximation clearly fails. However, these regions are very narrow for

ACT-1, and although phase errors are introduced because the exact connection problem has been neglected, the general picture is not significantly altered. The total electric field is then obtained by the Fourier sum over $k_{\perp}$.

Electric field amplitude calculated from this code is shown in Fig. 3(a) for cold ions, and Fig. 3(b) for hot ions ($T_i=0.5$ eV edge, 2 eV center), having held all other parameters fixed, for a set of launching frequencies. Four toroidal locations, ranging from $z=0$ cm (at the antenna toroidal position) to $z=195$ cm ($\sim$ half way around the machine), are depicted. Wave amplitude in Fig. 3(b) is seen to "track" the harmonic layer, represented by the dashed line $\omega/\omega_{ci}=6$, in a fashion very similar to the experimental data shown in Fig. 1. In particular, sharp interference structures can be seen which move through the "main cone" near the harmonic, as well as damping of the cone near the harmonic layer in the hot ion case. Mode converted hot plasma waves are responsible for features outside of, and at some frequencies on top of, the resonance cone remnants. These effects are absent for cold ions or unmagnetized ions.

In summary, the presence of a modification of the lower-hybrid wave trajectory, characterized by ion cyclotron periodicity, has been seen experimentally for the first time. We have shown that this feature is reproduced theoretically when mode conversion to the hot plasma wave with magnetized ions is taken into account. In a large tokamak LHW experiment, such as on PLT, the wave frequency is $f=20-40 f_{ci}$. But at the same time $k_{\perp} \rho_i$ is approximately five times larger than in ACT-1, so that similar effects should be present. However, due to the presence of a poloidal field and many closely spaced harmonic layers, the effects may be subtle and difficult to observe directly.

The authors would like to thank J. Taylor and W. Kineyko for their invaluable technical support, and T. Stix and V. Decyk for useful discussions. This work is funded by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073. F. Skiff is supported by a Fannie and John Hertz Foundation Fellowship.

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FIGURE CAPTIONS

FIG. 1 Radial probe scans of wave amplitude as a function of applied RF frequency, $\sim 120^\circ$ toroidally from the antenna, which was located radially at $r=6.5$ cm. Interference patterns can be seen in bands above ion cyclotron harmonics, as well as distortion and broadening of the resonance cone (main feature) near each harmonic layer. The innermost features are from waves travelling the long way around the torus.

FIG. 2 Ray tracing code results using experimental plasma parameters, for $\lambda_i = 4, 5, 9, 12, 15, 25$ cm ; at $f=41$ MHz. (13 ports = 180° around the torus). (a) Perpendicular wavenumber k_x vs. radial position. The shortest λ_i are heavily electron Landau damped, while longer λ_i mode convert from LHW + HPW + IBW, which are then ion cyclotron damped in front of the sixth harmonic layer. (b) Corresponding ray tracing trajectories. The characteristic "hook" pattern formed by outgoing hot plasma waves and inward propagating ion Bernstein waves is evident.

FIG. 3 Fourier reconstruction code results of waveform amplitudes for a range of launching frequencies, at four toroidal distances from the antenna for (a) Cold ions. (b) Hot ions. $T_i=0.5$ eV at $r=6$ cm plasma edge, increasing linearly to $T_i=2$ eV at $r=0$ cm, on axis.

Fig. 1

Fig. 2

$Z = 65 \text{ cm}$

$Z = 130 \text{ cm}$

$Z = 195 \text{ cm}$

Fig. 3