Observation of the backward electrostatic ion-cyclotron wave

J. Goree, M. Ono, and K. L. Wong
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

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The backward branch of the electrostatic ion-cyclotron wave has been observed for the first time. The wave, which was driven by a phased antenna structure inserted in a neon plasma, exists in the parameter ranges $2T_i/m_i \ll (\omega/k_\parallel)^2 \ll 2T_e/m_e$, $n\Omega_i < \omega < (n+1)\Omega_i$, $T_e \gtrsim T_i$, and $\omega_{pi} > \Omega_i$. Double-tip probe interferometry data agree with the theoretical dispersion relation. The antenna couples into the wave more readily on the side of the antenna where it has its smallest wavenumber.

I. HISTORICAL INTRODUCTION

The electrostatic ion-cyclotron wave is the hot magnetized plasma mode with its frequency near an ion gyrofrequency harmonic and a phase velocity parallel to the magnetic field $\omega/k_\parallel$ less than the electron thermal velocity, but greater than the ion thermal velocity. It has also been called the neutralized-ion Bernstein wave.[1]

The wave was discovered by D'Angelo and Motley,[2] who observed the acoustic-like forward wave at the fundamental frequency in a cold alkali plasma. Drummond and Rosenbluth[3] attributed their observation to a kinetic instability associated with parallel electron drift. Lominadze and Stepanov[4] introduced finite Larmor radius (FLR) effects into the theory, revealing for the first time this mode's backward branch.

These are the criteria which specify the electrostatic ion-cyclotron wave:

$$(2T_i/m_i)^{1/2} \ll \omega/k_\parallel \ll (2T_e/m_e)^{1/2}, \tag{1}$$

$$n\Omega_i < \omega < (n+1)\Omega_i, \quad n \geqslant 1, \tag{2}$$

and

$$\omega_{pi} > \Omega_i \text{ and } T_e \gtrsim T_i.$$

The real solutions of the dispersion relation of the electrostatic ion-cyclotron wave generally show two possible values for $k_\perp$ for a given frequency. Except for ω very near $n\Omega_i$, the shorter-wavelength solution is a backward wave, i.e., the wavenumber vector component $\mathbf{k}_\perp$ has the direction opposite that of the group velocity. Several experiments have been reported on the forward branch,[5–7] and Schmitt was able to observe effects of ion-cyclotron harmonics through antenna loading measurements.[8] However, observation of the backward branch was not reported in these experiments. This mode should be distinguished from both the pure ion Bernstein wave[1] which has no dependence on electron kinetics and has $\omega/k_\perp \gg \omega_{pe}/k_\perp$, and the more general cold electron, ion Bernstein wave,[9] which is characterized by $\omega/k_\parallel \gg (2T_e/m_e)^{1/2}$. The ion Bernstein modes are backward, and they have no forward branches.

II. DISPERSION RELATION

For electrostatic waves, the collisionless dispersion relation can be expressed[10] as $D(\omega, k_\perp) = 0$, where

$$D = k_\perp^{\,2} K_{xx} + 2k_\parallel k_\perp K_{xz} + k_\parallel^{\,2} K_{zz} \tag{3}$$

and the dielectric tensor elements are

$$K_{xx} = 1 + \frac{\omega_{pe}^2}{\Omega_e^2} + \sum_j \frac{\omega_{pj}^2\, e^{-\lambda_j}}{k_\parallel \omega\, \lambda_j}\left(\frac{m_j}{2T_j}\right)^{1/2} \times \sum_{n=-\infty}^{+\infty} n^2 I_n(\lambda_j) Z(\zeta_n^j),$$

$$K_{xz} = -\frac{k_\perp}{k_\parallel} \sum_j \frac{\omega_{pj}^2}{\omega\Omega_j} \frac{e^{-\lambda_j}}{\lambda_j} \sum_{n=-\infty}^{+\infty} n I_n(\lambda_j)\,[1 + \zeta_n^j Z(\zeta_n^j)],$$

$$K_{zz} = 1 + \frac{2\omega_{pe}^2}{k_\parallel^2} \frac{m_e}{2T_e}\left[1 + \frac{\omega}{k_\parallel}\left(\frac{m_e}{2T_e}\right)^{1/2} Z(\zeta_0^e)\right].$$

Here, $\lambda_j = k_\perp^{\,2} T_j / m_j \Omega_j^{\,2}$, j designates the ion species, I_n is the modified Bessel function, $\zeta_n^k = (\omega - n\Omega_k)(m_k/2T_k)^{1/2}/k_\parallel$, and Z is the plasma dispersion function. It was assumed that $\omega \ll \Omega_e$, $\lambda_e \ll 1$, and that the distribution functions are isotropic, nondrifting Maxwellians.

By specifying the parameters of inequalities (1) and (2), this dispersion relation yields the electrostatic ion-cyclotron wave solutions. It also yields the cold electron, ion Bernstein solutions[9] if the appropriate parameter $\omega/k_\parallel \gg (2T_e/m_e)^{1/2}$ is chosen instead of inequality (1). Except for the acoustic wave limit,[11] $\lambda_j \ll 1$, the roots of the dispersion relation are most easily computed numerically. For a single ion species, the wave is forward for small values of λ_i and backward for $\lambda_i \gtrsim 1$. For all values of λ_i, the electrostatic ion-cyclotron wave is prone to severe ion, and especially electron, Landau damping. The first term of Eq. (3) depends mostly on ion kinetics and one finds in it the FLR effects which are responsible for the backward wave. The second term is negligible, and the third term, because of electrons, dominates for the forward wave.

III. RESULTS

The experiment was run on the ACT-I toroidal device[12] with a vertically uniform magnetized plasma with warm ions. A singly ionized heavy ion species, Ne^+, was used to satisfy relations (1) and (2). Observation of the backward branch may have been unreported previously because it is difficult to satisfy these relations, to obtain warm ions, and to overcome Landau damping. Warm ions are necessary for FLR effects and thus for the existence of the backward branch. An antenna structure, constructed of two blades of molybdenum plate attached to 1 mm tungsten rod, was inserted into the plasma. The blades were parallel to the magnetic field, in a vertical plane, as shown in Fig. 1.

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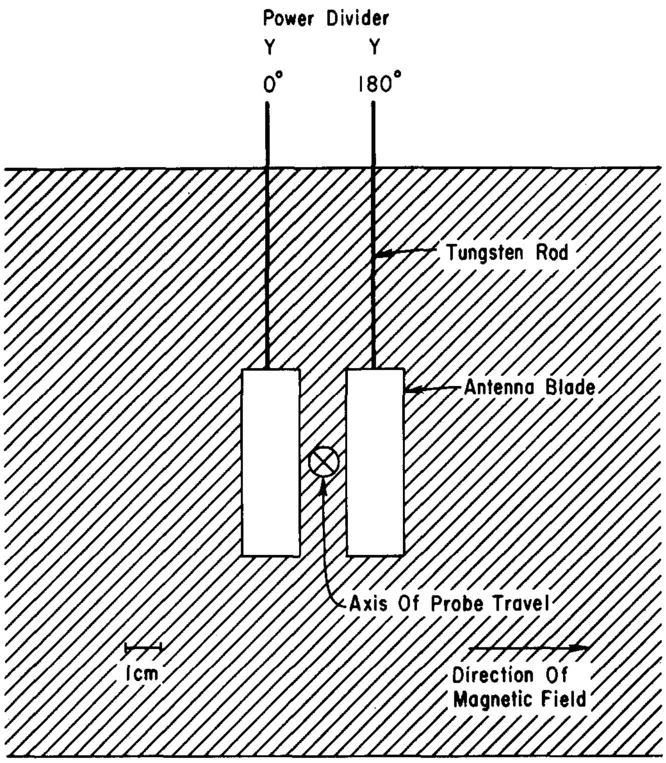

FIG. 1. The geometry of the antenna, drawn to scale, as viewed from the side of the torus. Plasma is shown shaded.

A rf signal of several volts was applied to the antenna, and the two blades were phased at 180° to create a $k_{\parallel}$ spectrum peaked at $1.0\ \mathrm{cm}^{-1}$. The wave launched in the plasma was detected by a rf double-tip Langmuir probe which was scanned radially to measure $k_{\perp}$ by interferometry. The probe could pass through the gap between antenna blades, where strong nonpropagating disturbance was found in a 1 cm thick layer. Outside this layer, the electrostatic ion-cyclotron wave was observed.

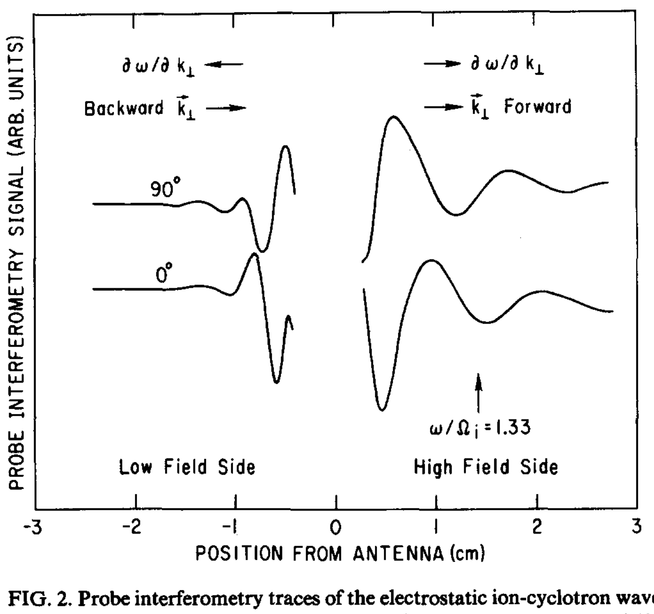

FIG. 2. Probe interferometry traces of the electrostatic ion-cyclotron wave in a neon plasma. The wave was launched with frequency $\omega/2\pi = 440$ kHz ($\omega/\Omega_i = 1.33$) on the fundamental mode branch. The traces were made while delaying the probe signal by either 0° or 90° compared to the oscillator driving the antenna. The direction of $\mathbf{k}$ points from valleys in the 90° trace to valleys in the 0° trace, and from hills in the 90° trace to hills in the 0° trace. The forward wave, by definition, has $\mathbf{k}_{\perp}$ in the same direction as the group velocity, which is always away from the antenna. The backward wave is seen at the left, on the low field side of the antenna. The strong nonpropagating disturbance between the antenna blades is not shown, for clarity.

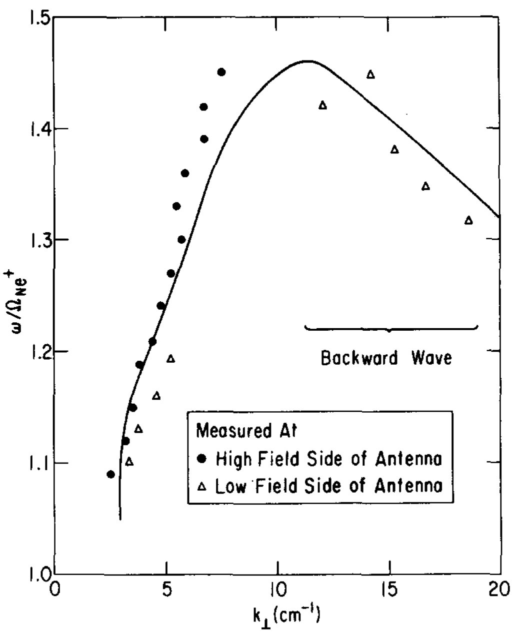

FIG. 3. The dispersion relation of the electrostatic ion-cyclotron wave in the same neon discharge used in Fig. 2. The solid curve is a numerical solution assuming $k_{\parallel} = 1.0\ \mathrm{cm}^{-1}$, $T_e = 2.1$ eV, $T_i = 0.4$ eV, $n_e = 3.6\times 10^9\ \mathrm{cm}^{-3}$.

The antenna blades lay perpendicular to the toroidal magnetic field gradient. The direction of this gradient affected the antenna coupling to the wave, and the backward wave was usually found on the low field side of the antenna. Using probe interferometry made with rf phase sensitive detector, we compared two radial interferometry traces, with the signal delayed by 0° and 90°, to determine the direction of $\mathbf{k}_{\perp}$. Here, $\mathbf{k}_{\perp}$ points in the direction in which the peaks and valleys of the 0° trace appear to be shifted from those of the 90° trace. The group velocity direction is always outward from the antenna, and the backward wave is identified when $\mathbf{k}_{\perp}$ is directed in toward the antenna. Such behavior is observed in the interferometry traces shown in Fig. 2. By taking data for many frequencies, we obtained the experimental dispersion relation shown in Fig. 3. A theoretical solution, Eq. (3), is also shown and the experimental data fit it well.

The backward wave propagates on the low field side of the antenna, and the forward wave on the high field side. This tendency was also observed for all other plasma conditions examined, although the forward branch often coupled on both sides, and the backward branch sometimes coupled on the high field side, but more weakly than on the low field side.

This interesting result, that the two modes tend to be launched in opposite directions, can be explained with Skiff's[13] one-dimensional model of linear antenna coupling theory for two modes, which shows that the power going into one of the two modes is inversely proportional to its wavenumber. Easier coupling is thus toward the left in the theoretical dispersion relation in Fig. 3. Since the vertical axis in Fig. 3 is normalized by the magnetic field strength, it is clear from following the curve that the backward mode has a smaller wavenumber toward the low field side. Therefore, if the backward mode is to couple at all, in competition with the more readily excited forward mode, it is expected to be observed mostly on the low field side where it has its smallest wavenumber. This explanation can generally be extended to other cases[13] where an antenna may excite two modes at a given frequency.

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