LETTERS

LOWER HYBRID WAVE EXCITATION BY A FAST WAVE CURRENT DRIVE ANTENNA

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ABSTRACT. Excitation of the lower hybrid wave (slow wave) using a launcher designed for fast wave excitation has been observed under conditions where neither direct excitation nor mode conversion is expected to take place. The slow wave was revealed through the presence of its resonance cone. The experiment was performed with $\Omega_i \ll \omega \ll \Omega_e$. The coupling of the fast wave into the slow wave is attributed to parasitic excitation, which is a linear mechanism involving electron $\vec{E} \times \vec{B}$ motion and charge separation in a density gradient. This process could be a significant loss mechanism for fast wave current drive in toroidal plasmas.

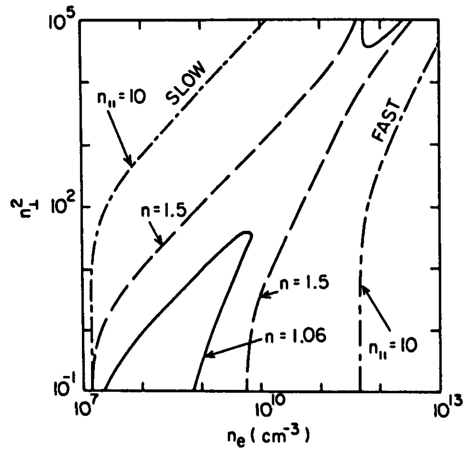

FIG. 1. Cold plasma dispersion relation. Solutions of the dispersion relation, showing the fast and slow modes, are shown for three values of $n_\parallel$, assuming $m_i = 20.18$ amu, $f = 32$ MHz, and $B = 4.0$ kG, which is appropriate for the low field side of the torus in the experiment. The experiment was carried out with $n_\parallel > 10$, while the dispersion relation exhibits mode conversion points for $1 < n_\parallel < 1.1$; mode conversion is thus not expected.

Fast wave current drive (FWCD) is unidirectional current generation that is created by damping of the fast magnetosonic wave (the fast wave) in the lower hybrid range of frequencies (LHRF), $\Omega_i \ll \omega \ll \Omega_e$. One reason for our interest in FWCD in toroidal plasmas is that it may allow current generation at densities exceeding the lower hybrid current drive density limit [1]. Experiments at several laboratories have demonstrated FWCD [2–5] with a fast wave launcher operated at frequencies $\omega \gtrsim 10\,\Omega_i$, where effects of ion cyclotron harmonics are negligible.

In recent JIPPT II-U and PLT experiments [6, 7], RF power applied to a fast wave launcher resulted in current drive. This current generation, however, exhibited many of the properties of the previous lower hybrid slow wave current drive experiments using the same frequency, including the density limit. The JIPPT II-U experimenters speculated that their antenna was actually coupling into the lower hybrid wave (slow wave), rather than the fast wave, by means of parasitic excitation, which is explained below. In this letter, we report an experiment that demonstrates that a fast wave antenna can, in fact, excite the slow wave, apparently through this mechanism.

The fast and slow waves are represented by solutions of the cold plasma wave dispersion relation [8] in the LHRF, as is shown in Fig. 1. Different polarizations (i.e. directions of the electric field $\tilde{E}$) and different wave vectors distinguish these two modes. To excite one and not the other, the launching structure is designed to produce the desired polarization. With antennas one does this by installing Faraday shields, which consist of metal strips covering the antenna, with slits between the strips oriented to transmit RF power with the desired polarization. The Faraday shields also usually serve to screen the antenna voltage from the plasma.

In the LHRF, the slow wave manifests itself through a resonance cone that is easily detected with an RF probe. A resonance cone is obtained from a spatially localized antenna if the mode frequency ω depends on the wavenumber $\vec{k}$ only through the ratio of its components, $k_\parallel/k_\perp$ [9]. This is true in the case of the lower hybrid wave where the electrostatic dispersion relation is $\omega = \omega_{\ell h}[1 + (m_i/m_e)(k_\parallel/k_\perp)^2]^{1/2}$, where $\omega_{\ell h}$ is the lower hybrid frequency [8].

The experiment was conducted with major radius R = 59 cm, limiter radius a = 7.5 cm, toroidal field B = 4.3 kG on axis, and no poloidal magnetic field. Access to the ACT-I plasma is obtained through 26 equally spaced ports on the low field side. We shall use the co-ordinate x, the depth into the plasma, where $x = a - r\cos\theta$ is defined to be zero at the outboard side limiter. Electron emission from a tungsten filament produced a neon plasma characterized by $T_e = 1.6$ eV.

To measure the density, we inserted an electrostatic antenna into the plasma at x = 4.5 cm and launched lower hybrid resonance cones, which we detected with a probe to determine that $n_e = 7.1 \times 10^9\ cm^{-3}$ at that location. This served to calibrate the ion saturation probe profile presented in Fig. 2. The fast wave is evanescent everywhere at these low densities.

The fast wave antenna was equipped with 10 mm wide grounded stainless steel Faraday shields with 2 mm gaps aligned in the $\hat{z}$-direction of the magnetic field, $\vec{B}$. They covered a 2.5 cm wide copper bar that carried RF current for a partial turn of 140° around the plasma, in the poloidal direction. Ceramic insulators completely covered the RF conductor and separated it from the Faraday shields. This antenna was used earlier in the FWCD demonstration reported in Ref. [2]; in that experiment, with $n_e \cong 3 \times 10^{12}\ cm^{-3}$, we confirmed that it launches the fast wave. The absence of a poloidal magnetic field in the ACT-I device ensured that the resulting RF electric field $\vec{\vec{E}}$ was orthogonal to $\vec{B}$.

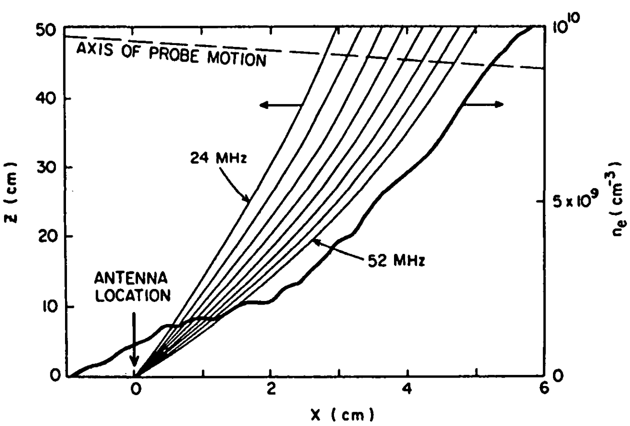

FIG. 2. Plasma density profile and ray tracing. The ion saturation current I_{sat} for a Langmuir probe is shown with a heavy line. To convert I_{sat} to density (right hand scale), the curve was calibrated at x = 4.5 cm, by using the lower hybrid resonance cone method of density measurement. By integrating the group velocity for the slow wave, using the density profile shown, trajectories of the resonance cones were calculated. Rays are shown, with the thin lines, for frequencies from 24 MHz to 52 MHz, in 4 MHz increments. The co-ordinate z of the left hand scale is the distance parallel to the magnetic field, assuming a two-dimensional slab geometry. The rays begin at the antenna, located at x = z = 0, and can reach the RF probe, located three ports away at the dashed line, which appears tilted owing to toroidicity.

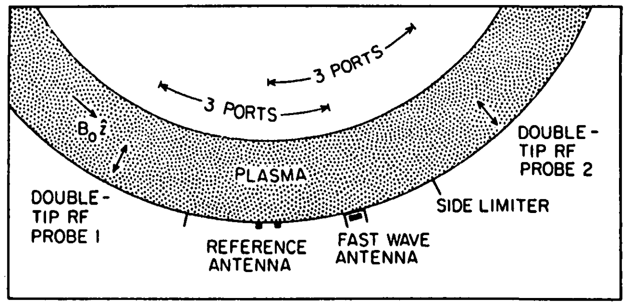

FIG. 3. Top view of antenna and probe layout. The edge of the toroidal plasma (the shaded region) is defined by a circular side limiter. On the low field side of the torus, the fast wave antenna and the reference antenna are located at the limiter radius. A double tip RF probe, which is capacitively coupled and employs differential signal detection, is located three ports (48. 2 cm) from each antenna. The axis of probe motion is shown by a double arrow.

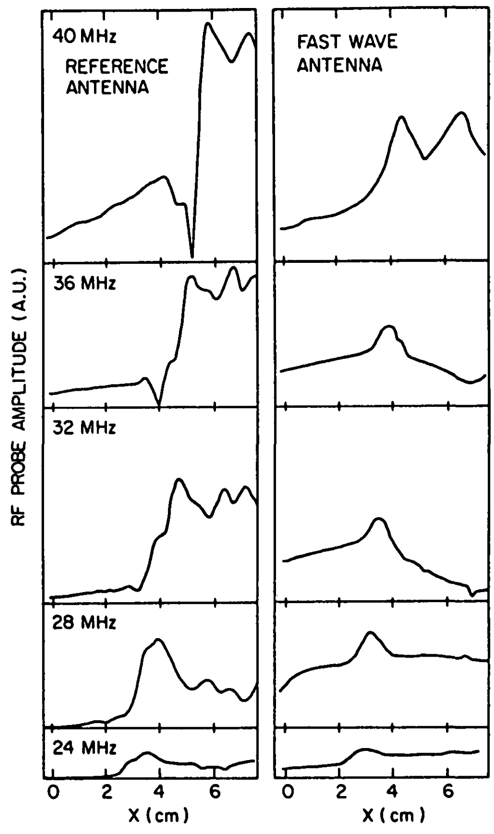

FIG. 4. Slow wave resonance cones. The radial profile of the RF probe signal amplitude was recorded for a series of frequencies f. Since the reference antenna has two elements, 180° out of phase, a null or minimum wave amplitude is expected at the centre of the resulting resonance cone; a single peak is expected from the fast wave antenna's single element. This figure demonstrates that the reference antenna, which is known to launch the slow wave, and the fast wave antenna both excite resonance cones.

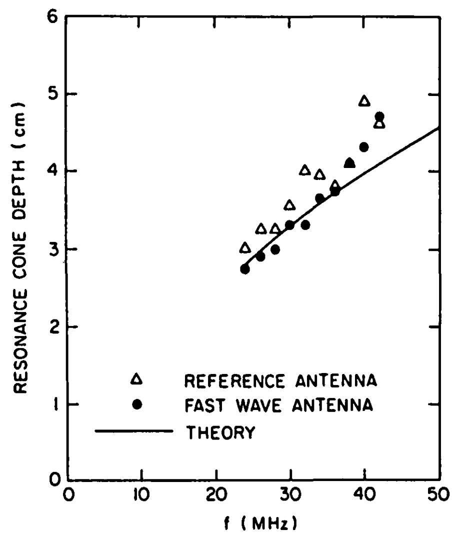

FIG. 5. Resonance cone depth x-dependence on frequency f. The experimental data points were obtained from Fig. 4, and the theoretical curve from ray tracing, as shown in Fig. 2. Random errors are ±1.5 mm, due to the breadth of the peaks in Fig. 4, and systematic errors are less than 4 mm. The resonance cones appear to originate near the antenna surface.

For comparison with the fast wave antenna, we located the electrostatic antenna, which we shall call the 'reference antenna', at the same depth as both the outboard side limiter and the fast wave antenna, x = 0, and three ports toroidally from an RF double tip electric probe, as is shown in Fig. 3. The reference antenna consists of two capacitively coupled vertical metal strips that are in contact with the plasma and are driven 180° out of phase to create a $k_\parallel$ spectrum peaked at 1 cm^{-1} with an FWHM of 1 cm^{-1}. This type of antenna has been shown to be an effective lower hybrid wave launcher [9]. The fast wave launcher, which has no phased structure, is expected to produce a $k_\parallel$ spectrum that has a broad peak centred at 0 cm^{-1}; this antenna was also located three ports from a probe. The antennas were powered one at a time with a sinusoidal RF signal in the frequency range 24–50 MHz, at an intensity too low either to disturb the discharge or to allow parametric decay. Signals from both antennas were recovered from the noise without difficulty. We detected the signal using an RF lock-in amplifier synchronized to the wave frequency, with a 10 Hz bandwidth.

The plots of the RF probe signal amplitude versus depth x shown in Fig. 4 reveal the presence of resonance cones. The cones are identifiable, but are not so clear as cones launched from an antenna in the centre of the plasma; we usually find this to be the case with externally launched lower hybrid waves. Identifying the peak of the resonance cone and plotting its position versus frequency yields Fig. 5, where a comparison with theory is displayed. We derived the theoretical curve in Fig. 5 from the ray tracing shown in Fig. 2.

The chief observation to be made from Figs 4 and 5 is that the wave structures excited by the fast wave antenna and the reference antenna are similar and exhibit the same relation between depth and frequency. Since the reference antenna is known to launch the slow wave, we conclude that the fast wave antenna has also launched the slow wave.

Having established that the fast wave antenna couples into the slow wave, we shall now determine how this takes place. There is no mode conversion point, given the range of $n_\parallel$ and n_e, as can be determined from Fig. 1; therefore, mode conversion cannot be responsible. Scattering from drift waves can be excluded because the signal did not have a shifted frequency. Two other mechanisms for excitation that are left to consider are parametric decay and electrostatic excitation. We observed no evidence of parametric activity, thus parametric decay is ruled out. Electrostatic excitation can be excluded by considering that we used a Faraday shielded antenna that was previously shown to be very effective in suppressing electrostatic fields in this frequency range [10].

Another process that could convert RF power from the fast wave polarization into the slow wave polarization is parasitic excitation, which is scattering due to gradients of plasma parameters [10, 11]. The slow wave is parasitically excited if there is either a gradient in density and, therefore, in the $\vec{\tilde{E}} \times \vec{B}$ term, iD, of the dielectric tensor or a gradient in the fast wave field $\tilde{E}_y$. We found from Fig. 5 that the slow wave excitation region is near the antenna surface, where the plasma density gradient and the gradient in the evanescent field of the antenna are large, which is consistent with the parasitic excitation process. This linear process occurs when the particle $\vec{\tilde{E}} \times \vec{B}$ motion, in response to the fast wave's electric field $\tilde{E}_y$, is parallel to the direction of the gradient in an inhomogeneous plasma that is magnetized in the $\hat{z}$-direction. In the LHRF, ion $\vec{\tilde{E}}_y \times \vec{B}$ motion is negligible; thus, charge separation results from the electron motion. The charge separation produces an oscillating electric field that has the $\hat{x}$-polarization of the slow wave, thereby exciting the slow wave. Skiff et al. demonstrated parasitic excitation in the ion cyclotron range of frequencies, where the fast wave is the same, but the slow wave is a hot plasma mode, the ion Bernstein wave [11].

In predicting the efficiency of FWCD, parasitic excitation must be included as a loss term for large tokamaks because the slow wave cannot penetrate to regions of high density as the fast wave does. The results presented here do not indicate the fraction of RF power that is converted to the slow wave by parasitic excitation nor do they demonstrate that parasitic excitation was the only cause of coupling into the lower hybrid wave in the PLT and JIPPT II-U experiments. The results simply indicate that the process can take place in the LHRF. To find the coupling efficiency in the LHRF, it would be necessary to integrate the Maxwell–Vlasov equations, as was done in Refs [10, 11], for the plasma parameters of each experimental problem.

If the parasitic excitation of the slow wave is a serious problem, a possible solution might be using a lower frequency so that $\omega_{\ell h}/\omega > 1$ at the antenna, preventing the slow wave from propagating. This was done in the FWCD experiment cited in Ref. [2], when we observed current drive far beyond the density limit for slow wave current drive. There, we used a frequency of 18 MHz so that $\omega_{\ell h}/\omega \cong 10$.

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