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ECHO PHENOMENON ASSOCIATED WITH
LOWER-HYBRID-WAVE LAUNCHING

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ABSTRACT

Lower hybrid waves at two different frequencies f_1 and f_2 are launched simultaneously from two localized antennas, and a third wave is observed to arise near the plasma edge at the frequency $f = f_2 - f_1$. This phenomenon can be explained by an echo effect near the plasma surface.

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Lower hybrid waves are important in thermonuclear fusion research primarily because of their possible applications to plasma current drive and heating in tokamaks. They can be launched by imposing a macroscopic electric field near the plasma surface with metal waveguide arrays at high power density ($\sim 10 \text{ kW/cm}^2$). Reactor studies¹ show that in a tokamak fusion reactor with lower hybrid wave current drive and heating, about 1% of the total first wall area will be used for wave launching. In other words, there will be more than one antenna, possibly driven at different frequencies, and it is interesting to examine how these waves, from various antennas, interact with one another. In this letter we present experimental data showing that lower hybrid waves launched from two separate antennas at various frequencies f_1 and f_2 can excite a third wave at the beat frequency $f_2 - f_1$. This third wave has a parallel phase velocity near the electron thermal velocity so that it is strongly damped near the plasma surface via electron Landau damping. With respect to Controlled Thermonuclear Reaction (CTR) applications including current-drive and plasma-core heating, this nonlinear process may represent a source of operating inefficiency.

The experiment was performed in the Princeton ACT-1 device² working with a hydrogen plasma and the following parameters: magnetic field on axis = 2.8 kG, neutral pressure $\leq 10^{-5}$ torr (gauge), plasma density varying from $3 \times 10^8 \text{ cm}^{-3}$ to 10^{10} cm^{-3} , and electron temperature $\sim 1 \text{ eV} - 2 \text{ eV}$. The plasma was produced by a heated tungsten filament as described

previously.² Figure 1(a) is a schematic drawing of the experimental setup. The lower hybrid waves were launched from electrostatic plates at the plasma edge. Two of twelve plates were driven at two frequencies f_1 and f_2 . The excited lower hybrid waves propagate along resonance cones as shown in Fig. 1(b). In addition to the excited waves at frequencies f_1 and f_2 , the probe picks up a signal at the beat frequency $f = f_2 - f_1$ near the plasma edge. In order to avoid mixing effects inside the probe sheath, the driving signals were kept at very low power levels (approximately 1 mW). The probes detect the beat signal only when $f_2 > f_1$. When we switch the two oscillators, the signal disappears as shown in Fig. 1(c). This interesting asymmetry suggests that the signal may be the second order echo associated with the driven waves at f_1 and f_2 .

The first reports of plasma wave echoes, by Gould, O'Neill, and Malmberg,³ were followed by a series of elegant experiments⁴⁻⁷ which demonstrated the reversibility of Landau damping. It was also shown⁶ that the ballistic term in the echo field can dominate over the resonance term so that the phase velocity of the echo field corresponds to the velocity at which the electron distribution function has the steepest slope. The $(m+n)$ th order echo, with frequency $f_{mn} = n f_2 - m f_1$, appears at the position $z_{mn} = n f_2 \cdot \ell / f_{mn}$ where ℓ is the separation between the two antennas as shown in Fig. 2(a). For a second order echo, $m = 1$, and $n = 1$, and

$$f_{11} = f_2 - f_1 , \quad (1)$$

$$z_{11} = f_2 \cdot \lambda / (f_2 - f_1) . \quad (2)$$

The echo appears only on one side of the antenna, as observed in the experiment. Moreover, the peak of the signal should appear at the location predicted by Eq. (2). In the absence of toroidally scanning probes, we picked various combinations of antenna plates, probes, and frequencies to cover a wide range of $(z - z_{11})$ in small steps. In Fig. 2(b), the echo amplitude is plotted versus $(z - z_{11})$. Despite considerable scatter in the data points, due to variation in the coupling efficiencies among the various plates and to different probe sensitivities, it is clear that the echo amplitude peaks near $z = z_{11}$. This echo phenomenon may be similar to that reported by Leppert et al.⁸ who were apparently not aware of the electrostatic nature of lower hybrid waves propagating along resonance cone⁹ trajectories. Since the echo field is a macroscopic electric field at the plasma edge, it may excite lower hybrid waves that propagate into the plasma interior. Figure 2(c) shows simultaneous interferometric measurements with two neighboring probes. The signal detected by probe #1 should propagate along the resonance cone trajectory and reach probe #2 at the location marked by the arrow. The data show that the wave is damped near the plasma surface so that it does not reach probe #2. The interferometry yields

the perpendicular wavenumber $k_{\perp}$, and the parallel wavenumber, $k_{\parallel}$, can then be calculated from the lower hybrid wave dispersion relation:

$$k_{\parallel} = k_{\perp} \cdot f/f_{pe} \cdot (1 + f_{pe}^2/f_{ce}^2)^{1/2}, \quad (3)$$

where f_{pe} and f_{ce} are the electron plasma and cyclotron frequencies, respectively. Here f_{pe} is determined from the electron density measured by the resonance cone technique.⁹ It is found that the parallel phase velocity for the echo field has an approximate value of 10^8 cm/sec $\sim 1.5 V_{Te}$ where V_{Te} denotes the electron thermal velocity. When the edge plasma density is raised from 3×10^8 cm⁻³ to 2×10^9 cm⁻³, $k_{\perp}$ increases in such a way that $\omega/k_{\parallel} \sim 1.5 V_{Te}$ remains unchanged. This is also true when we vary the echo frequency $f = f_2 - f_1$. Therefore, the parallel phase velocity of the echo wave always has a value at which there is a steep slope in the electron distribution function, similar to previous ballistic echo experiments.⁶ This condition results in strong electron Landau damping so that the echo wave cannot penetrate into the plasma interior.

In summary, we have demonstrated in laboratory experiments that, as a result of the echo phenomenon, two lower hybrid waves at different frequencies can excite a third wave which is damped near the plasma surface. Unlike other well-known nonlinear phenomena associated with lower hybrid waves, namely,

various parametric decay processes¹⁰ and ponderomotive force effects,¹¹ the echoes can appear at very low power levels in a collisionless plasma. The process reported here may represent a source of inefficiency for CTR lower-hybrid current-drive or plasma heating. To assess the importance of this loss, however, it will be necessary to determine the degree of energy transfer to the echoes at high power levels.

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FIGURE CAPTIONS

FIG. 1. Observation of Echo

- (a) Schematic drawing of experimental setup.
- (b) Amplitude profile of the excited resonance cones detected by probe #1 ($f_1 = 50$ MHz, $f_2 = 95$ MHz).
- (c) Echo signal appears at probe #1 only when $f_2 > f_1$.

FIG. 2. Verification of Echo

- (a) Simplified picture of the experiment.
- (b) Variation of the echo amplitude at frequency $f_2 - f_1$ as a function of $z - z_{11}$. Here f_1 varies from 50 MHz to 52 MHz, f_2 varies from 74 MHz to 90 MHz, z varies from 10 cm to 17 cm.
- (c) Echo signal detected by two neighboring probes. The arrows indicate the corresponding wave packet locations if the wave were not damped. $f_1 = 50$ MHz, $f_2 = 82$ MHz.

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Fig. 1

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