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Excitation of Fast Waves near the Mean Gyrofrequency

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Fast waves with frequencies near the mean gyrofrequency $[\omega \sim (\omega_{ci}\omega_{ce})^{1/2}]$ were excited in a toroidal, magnetized plasma. Experimental measurements were made of wavelengths and phase velocities perpendicular to the toroidal magnetic field, and wave energy trajectories in the plasma, with varying wave frequency, plasma density, and magnetic field values. Experimental results agree with predictions from the cold-plasma dispersion relation.

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Few experimental studies of the fast wave in the frequency regime $\omega_{ci} \ll \omega \ll \omega_{ce}$ have been done.[1-3] However, with the success of slow-wave lower-hybrid current drive in toroidal devices, considerable interest is developing for fast-wave current drive. Fast-wave current drive has been reported recently for cases of toroidal eigenmode excitation[2] and unidirectional phased-array-launched fast waves.[3] Knowledge of the fundamental wave properties of the fast wave would help in planning current-drive experiments. For example, in slow-wave experiments in tokamaks there is controversy about the wave numbers of the propagating wave; hence, it is of interest to determine if the fast wave in the same frequency regime propagates in a torus according to cold-plasma dispersion-relation predictions. In this Letter we report experimental measurements of the fast wave near the mean gyrofrequency. Measurements show the forward nature of the phase velocity, group velocity direction and energy flow, and radial wavelengths, all in agreement with theoretical predictions.

Cold-plasma dispersion-relation and wave-coupling predictions for the fast wave have been made.[4-6] The wave is right-hand polarized and satisfies the dispersion relation

$$n_r^2 \approx \frac{\varepsilon_{xy}^2 - (n_z^2 - \varepsilon_\perp)^2}{n_z^2 - \varepsilon_\perp + \varepsilon_{xy}^2/\varepsilon_\parallel} - n_\theta^2, \qquad (1)$$

for $1 \ll \varepsilon_\perp \ll \varepsilon_{xy} \ll \varepsilon_\parallel$ when $n_\theta \sim n_z$, where

$$\varepsilon_\perp \approx 1 + \omega_{pe}^2/\omega_{ce}^2 - \omega_{pi}^2/\omega^2, \quad \varepsilon_\parallel \approx 1 - \omega_{pe}^2/\omega^2,$$

$$\varepsilon_{xy} \approx \omega_{pe}^2/\omega\omega_{ce},$$

and $\mathbf{B}_0 = \mathbf{B}_{\text{toroidal}} = B_0\hat{\mathbf{z}}$, $n_r = ck_r/\omega$, $n_z = ck_z/\omega$, $n_\theta = ck_\theta/\omega$. Equation (1) is a slab-geometry approximation and would be invalid when radial-focusing effects become important.

For the experimental regime described below the radial wave number is

$$k_r = \frac{2\pi}{\lambda_r} \approx \frac{\omega\omega_{pe}^2}{c^2 k_z \omega_{ce}} \left(1 - \frac{2\omega^2\omega_{pe}^2}{c^2 k_z^2 \omega_{ce}^2}\right)^{-1/2}. \qquad (2)$$

For $k_r/k_z \gg 1$ the phase velocity is radially inward from the antenna at an angle of $\pi/2 - \alpha$ with respect to the magnetic field, where

$$\tan\alpha \approx \frac{c^2 k_z^2 \omega_{ce}}{\omega\omega_{pe}^2} \left(1 - \frac{2\omega^2\omega_{pe}^2}{c^2 k_z^2 \omega_{ce}^2}\right)^{1/2}$$

with magnitude

$$v_\phi \approx \frac{c^2 k_z \omega_{ce}}{\omega_{pe}^2} \left(1 - \frac{2\omega^2\omega_{pe}^2}{c^2 k_z^2 \omega_{ce}^2}\right)^{1/2}. \qquad (3)$$

The wave energy will flow at angle θ with respect to the magnetic field given by

$$\tan\theta = \frac{v_{g_r}}{v_{g_z}} \approx \frac{c^2 k_z^2 \omega_{ce}}{\omega\omega_{pe}^2} \left(1 - \frac{2\omega^2\omega_{pe}^2)}{c^2 k_z^2 \omega_{ce}^2}\right)^{3/2}. \qquad (4)$$

The relation between group and phase velocities is shown graphically in Fig. 1.

The experiments reported here were performed on the Irvine Torus. This device has a major radius of $R = 56$ cm with minor-radius limiters set at $a = 3.7$ cm. The plasma is formed by toroidally symmetric electron beams thermionically emitted from tungsten filaments.[3] The steady-state beams circulate in both directions around the torus, ionizing argon gas injected into the vessel. Densities of $n_e \leq 3\times10^{13}$ cm^{-3} with $T_e < 15$ eV have been obtained by this method. These experiments were performed at densities near $n_e \approx 2\times10^{12}$ cm^{-3} with a neutral-argon pressure of 8.4×10^{-5} Torr. To satisfy the

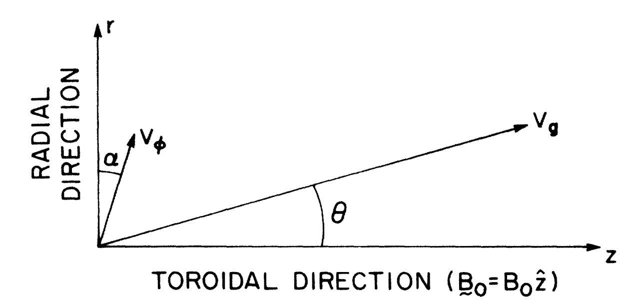

FIG. 1. Directions and relative magnitudes of phase and group velocities.

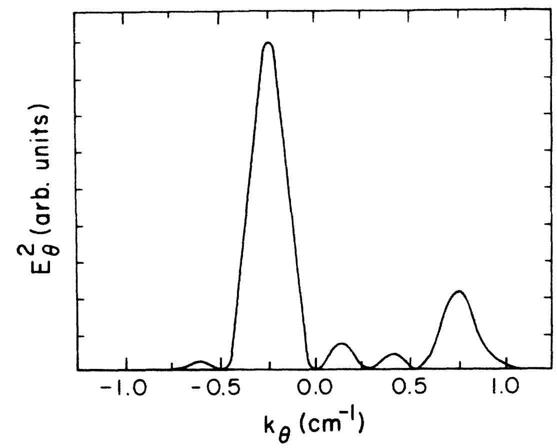

FIG. 2. Calculated azimuthal free-space power spectrum for phased-array antenna; 23-cm principal wavelength, $\pi/2$ phase shift between adjacent antenna elements.

fast-wave cutoff and accessibility conditions, the steady-state toroidal magnetic field was 0.75 kG$\leq B_\phi \leq$1.6 kG. There is no Ohmic transformer pulse and hence the rotational transform is zero. A single-tip, coaxial rf probe, movable radially, was used for interferometry and wave-amplitude measurements. The probe was positioned toroidally 3.5 cm from one end of the fast-wave antenna. A Langmuir probe was used to infer plasma density and electron temperature.

The fast waves were excited by a sixteen-element phased-array antenna,[3] which produced primarily the E_θ required for fast-wave launching. The calculated free-space power spectrum for this antenna with $\pi/2$ phase shifts between adjacent elements is shown in Fig. 2. Appropriate phasing of the antenna allows unidirectional wave launching, chosen in this case to be toward the rf probe. The principal indices of refraction excited are

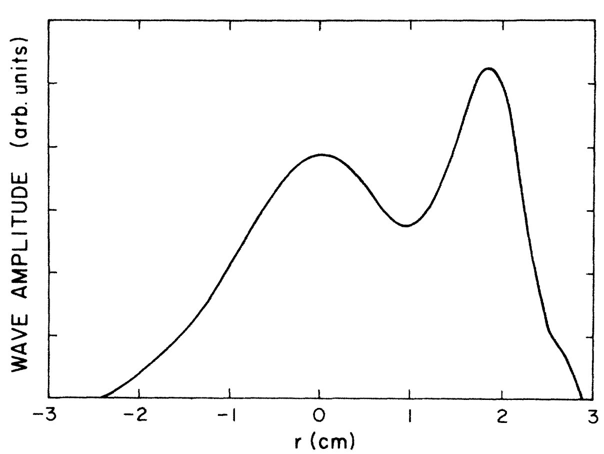

FIG. 3. Horizontal scan of fast-wave amplitude vs radial position. Inside limiter at $r=+3.7$ cm.

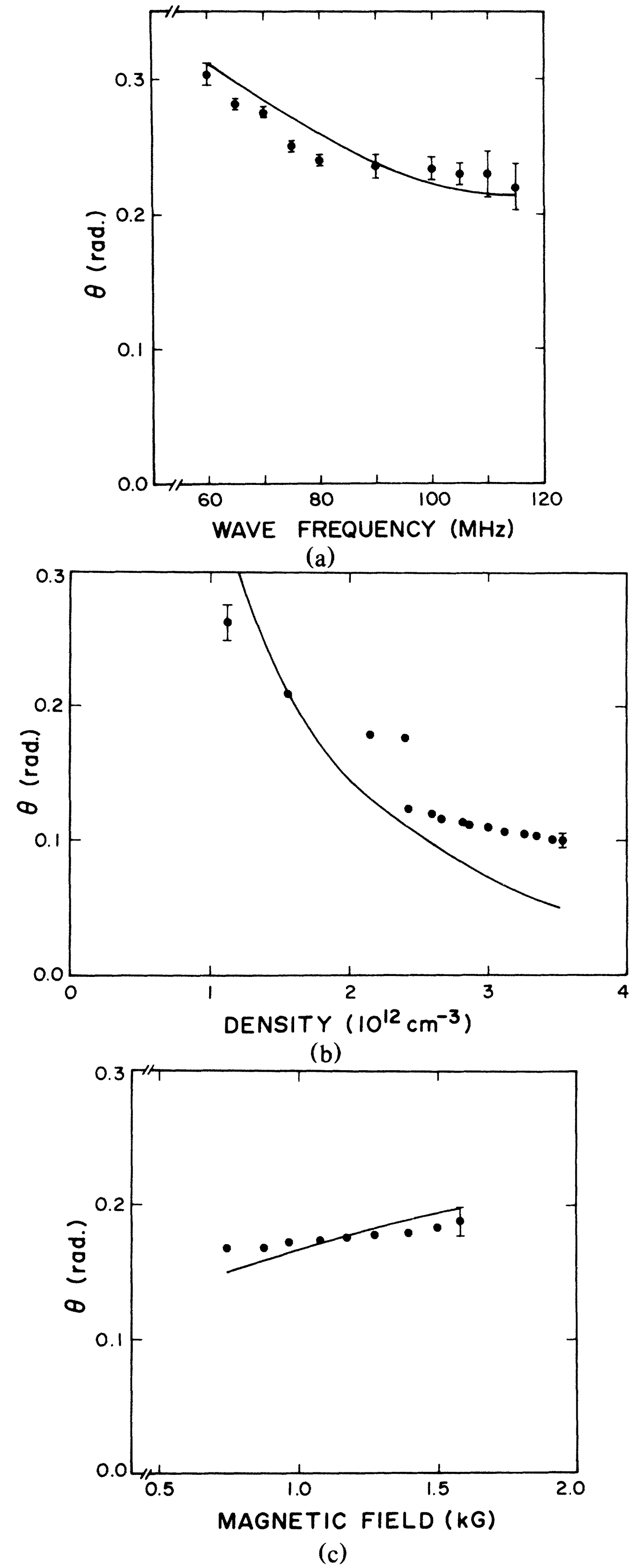

FIG. 4. (a) θ vs wave frequency; $B=1$ kG, $n=1.6\times10^{12}$ cm^{-3}. (b) θ vs plasma density; $B=1$ kG, $f=97$ MHz. (c) θ vs magnetic field; $n=2.2\times10^{12}$ cm^{-3}, $f=97$ MHz.

$n_\theta = 14.5$ and $n_z = 10.6$ at a frequency of $f = 94$ MHz.

For small θ, the group velocity is predicted to be at an angle

$$\theta \approx \frac{c^2 \omega_{ce} k_z^2}{\omega \omega_{pe}^2} \left(1 - \frac{2\omega^2 \omega_{pe}^2}{c^2 k_z^2 \omega_{ce}^2} \right)^{3/2} \quad (5)$$

with respect to the toroidal magnetic field. Hence, the wave energy will spread in the plasma according to the spread in the wave k_z spectrum. The energy does not propagate in the resonance cones of the slow lower hybrid wave, yet near the antenna the energy is localized radially and in a radial wave-amplitude scan the principal wave number will dominate. Figure 3 shows a radial wave-amplitude scan taken near the antenna before much radial spreading of the wave amplitude has occurred. There are two peaks in the radial scan, which are to be expected since the antenna is coaxial with the plasma. One peak is farther out than the other, which may be attributed to the observed peaking of the plasma density toward the inside of the plasma torus. One may determine θ for the principal excited wave number from Fig. 3 by measuring the radial position of the wave peak and the toroidal location of the center of the antenna (note that this is an average θ over the propagation path). Figure 4 shows θ measured as a function of wave frequency, plasma density, and magnetic field. The solid lines are numerical calculations from Eq. (4) using the measured density profiles and magnetic field, and the calculated principal k_z excited by the antenna. Outside the parameter range shown, cutoff and accessibility limits require more than one variable to be changed in this experiment for the fast wave to propagate. For example, in Fig. 4(a), below 60 MHz cutoff occurs and above 115 MHz accessibility stops wave penetration into the plasma, each of which may be circumvented by changing the magnetic field or antenna spectrum while changing wave frequency. For the experimental conditions, the leading term in the propagation angle has $\theta \propto k_z^2 B/\omega n_e$, which may be used for intuitive comparison with the figures, while the solid lines include the more complete numerical calculations. There is generally good agreement between experiment and cold-plasma theory for the fast-wave energy trajectory.

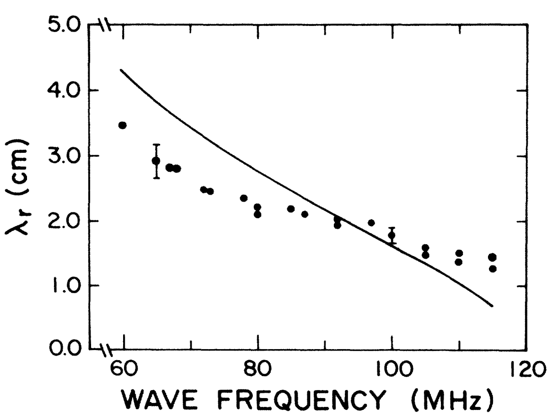

FIG. 5. Radial wavelength vs wave frequency; $n = (2.5-3.0) \times 10^{12}$ cm^{-3}, $B = 1$ kG.

Radial interferograms yielded λ_r information. Figure 5 shows measured radial wavelengths as a function of fast-wave frequency. The solid line is the prediction from Eq. (2) for the principal wave number. The radial component of the wave phase-velocity pseudovector should be directed into the plasma (in the same direction as the radial component of the group velocity). By the introduction of a variable delay line in the detection leg of the interferometry circuit, both the direction and magnitude of the phase velocity were found to agree with theoretical expectations; that is, the wave is a forward-propagating wave with $V_{\phi r} \approx f\lambda_r$ since $k_r^2 \gg k_z^2, k_\theta^2$. The slow wave would be the opposite, namely, a backward wave.

In summary, we have observed fast waves excited by a phased-array antenna with frequencies near the mean gyrofrequency. Experimental determinations of radial wavelengths, group velocity direction and energy flow, and phase velocity magnitude and direction are in agreement with cold-plasma theoretical predictions.

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[1]L. Olson, R. McWilliams, J. Glanz, and R. W. Motley, Nucl. Fusion **24**, 1085 (1984).

[2]J. Gorhee, M. Ono, P. Colestock, R. Horton, D. McNeill, and H. Park, Phys. Rev. Lett. **55**, 1669 (1985).

[3]R. McWilliams and R. C. Platt, Phys. Rev. Lett. **56**, 835 (1986).

[4]V. E. Golant, Zh. Tekh. Fiz. **41**, 2492 (1971) [Sov. Phys. Tech. Phys. **16**, 1980 (1972)].

[5]K. Theilhaber and A. Bers, Nucl. Fusion **20**, 547 (1980).

[6]R. McWilliams and Y. Mok, Fusion Technol. **7**, 283 (1985).