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FAST AND SLOW WAVES LAUNCHED FROM A FAST-WAVE WAVEGUIDE ARRAY

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ABSTRACT. Using a waveguide array designed to excite only fast-wave polarization, both slow and fast waves were observed in a toroidal plasma. The relative energy in the two modes was found to be a function of the plasma density, indicating that fast-wave current drive experiments should be performed at densities well above the calculated fast-wave cut-off density.

The two cold plasma waves in the lower hybrid frequency range, the slow and fast waves, have been used in many current drive experiments in tokamaks. For slow waves, a frequency dependent plasma density limit is observed above which current drive efficiency rapidly falls [1], identifying reactor relevant operation in the frequency range of a few GHz. According to basic plasma wave theory, fast waves should propagate in higher density regions and therefore should drive currents for plasma densities far above the slow-wave limit. These predictions of fast-wave propagation and current drive have been verified in experiments on the Irvine Torus [2]. Recent experiments on JFT-2M and JIPP T-IIU show fast-wave electron heating at densities more than a factor of ten above the fast-wave cut-off density [3, 4]. Some experiments to determine the current drive efficiency for fast waves in tokamaks have produced ambiguous results, often suffering a current drive density limit similar to that observed with slow waves [5-7].

There are several possibilities for the current drive density limit seen when fast-wave antennas were excited in tokamaks:

- (1) Slow waves were launched from the fast-wave designed waveguides [8, 9];
- (2) Fast and slow waves were launched, but slow waves dominated the particle motion;
- (3) Fast waves alone were launched, but were quickly converted in the plasma to slow waves [7, 10];
- (4) The frequency chosen was below the cut-off limit for fast waves in the tokamak plasma.

As a first step towards understanding which of these explanations is valid, four waveguides from the PLT

fast-wave current drive experiment were obtained and fitted into the Irvine Torus. In the PLT, the slow-wave density limit was found when fast waves were expected to be launched with these waveguides [6], but run time limitations prevented a thorough exploration of the physics involved. The simplicity of the Irvine Torus permits direct measurements of wavelengths and phase velocities [11], which gives confirmation of the specific role of fast and slow waves in the experiment. Previous work at Irvine, using a strap antenna, showed that a fast-wave antenna drove currents at densities above the slow-wave density limit [2]. At densities below the fast-wave cut-off, slow waves were observed in the plasma when the strap antenna was excited at the same frequency.

The present experiments were performed on the Irvine Torus with a major radius $R = 55.6$ cm. The helium plasma density could be varied from 10^{10} to 10^{12} cm^{-3} for these experiments. The plasma density was approximately uniform across the radius from the mouth of the waveguides through the region where wave propagation was studied. The density was measured with a Langmuir probe and compared with lower hybrid resonance cone measurements near 30 MHz. The normalized density fluctuations were about 10% throughout the plasma, which are similar to levels found in tokamak edge plasmas. The electron and ion temperatures were approximately 10 eV and 0.05 eV, respectively. A toroidal field of 1.0 kG was chosen so that plasmas with densities above and below the fast-wave cut-off density could be studied easily. The magnetic field varied less than 8% over the region of measurements. Therefore, the ratio of the major radius of the measurement point to that of the launching position does not account for the upshift in toroidal phase velocity N_z that is reported.

The waveguides were inserted into the helium plasma with graphite limiters flush at the ends of the waveguide array. The one by four array, taken from the PLT fast-wave array [6], has four guides aligned in a row along the toroidal (z) direction so as to impose a vacuum wave field in the poloidal (y) direction which would excite solely the fast-wave polarization in the plasma immediately in front of the antenna. Each guide element was 5.2 cm high by 8.4 cm in the toroidal direction. The array was excited at 800 MHz so as to impose a principal N_z of 2.2 for π phasing between adjacent antenna elements at the face of the waveguides. Bench measurements also gave an $N_z = 2.2$ in agreement with values calculated from the array geometry.

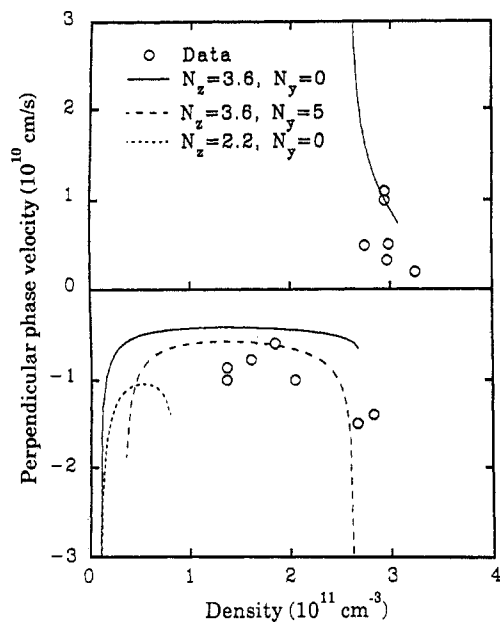


FIG. 1. Phase velocities of the observed waves as a function of plasma density. Fast waves have positive phase velocities, slow waves negative ones. The circles represent data and the lines theoretical results.

Electric field probes placed in ports separated toroidally but near the waveguides allowed diagnosis of the waves propagating in the plasma. The toroidal positions of the probes placed them well outside the measured vacuum near-field structure of the waveguide array. The probes could be moved radially to measure the local radiofrequency (RF) intensity in the plasma and also were used for interferograms, giving wave phase information. There was a background random RF amplitude across the plasma, which may be contributed to by scattered multiple pass signals, but coherent interferograms could be taken near the waveguides anyway. The phase velocity was measured by comparing interferograms with different phase delays in the reference signal. As a result, radial wavelengths, angle of propagation and direction of wave phase velocity were obtained. The direction of the phase velocity determined whether fast or slow modes were found in the plasma.

The main experimental results are displayed in Fig. 1, which shows the phase velocities of the observed waves as a function of plasma density. The cut-off density for 800 MHz slow waves is $8 \times 10^9 \text{ cm}^{-3}$. Hence, antennas which produce the polarization for slow waves may be expected to launch slow waves into plasmas above this density. The cut-off density for the fast wave is about $7.5 \times 10^{10} \text{ cm}^{-3}$

for the principal N_z of 2.2 estimated for the waveguide array used on the Irvine Torus. No waves were observed for densities below $1.3 \times 10^{11} \text{ cm}^{-3}$. Thus, the waveguide array does not excite slow waves directly in the plasma, in accord with expectations based on the antenna polarization.

Although the antenna is oriented to excite only fast waves, for densities from $1.4 \times 10^{11} \text{ cm}^{-3}$ to $2.7 \times 10^{11} \text{ cm}^{-3}$ only slow waves were seen in the plasma. Because the slow wave is not launched directly by the antenna, there must be some mechanism by which the plasma rotates part of the wave electric field into the direction necessary for slow wave propagation. Additionally, because of accessibility constraints, waves with $N_z = 2.2$ should not get into plasmas with densities greater than $8.3 \times 10^{10} \text{ cm}^{-3}$. As the plasma density increases, larger N_z values are required for accessibility, in particular $N_z = 3.6$ is required for accessibility at $n = 3 \times 10^{11} \text{ cm}^{-3}$. This value is substantially larger than 2.2 and, from a power spectrum estimate, less than one tenth of the power is expected to be generated at $N_z = 3.6$ or higher. In this case, without a scattering mechanism, waveguide power coupled to the plasma should decrease as the plasma density increases. However, the slow wave amplitudes did not differ by more than a factor of 0.5 over the entire range of observed densities and, in fact, increased slightly with increasing density. This result suggests that some mechanism in the plasma is required to rotate the wave electric field into the slow wave polarization. Such a mechanism would make possible the scattering of some perpendicular phase velocity N_{\perp} into N_z . Since N_{\perp} is expected to be much larger than N_z for both the fast and the slow waves, the scattering of a small fraction of N_{\perp} into N_z could lead to the N_z values necessary to satisfy accessibility requirements [10]. If slow wave excitation is due to scattering of the fast wave, then below the fast-wave cut-off density slow waves should disappear. An upshift in N_z may increase the fast-wave cut-off density and thereby increase the density at which scattered slow waves appear.

Because of the different propagation properties of slow and fast waves, waves of positive and negative phase velocity were observed at separate radial locations in the plasma. At densities above $2.7 \times 10^{11} \text{ cm}^{-3}$, the observation of positive phase velocity indicates that the fast wave propagates in the plasma, as shown in Fig. 1. The calculation of the minimum accessible N_z ($N_z = 3.6$) at this density is used for the theoretical curve in the figure [8, 9]. Hence the fast wave is observed in the plasma, but only at densities more

than three times the cut-off density estimated for this antenna.

In conclusion: Both slow and fast waves were observed in the plasma when the waveguide array was excited. However, there appears to be a substantial shift in N_z from the calculated spectrum of the antenna. The calculated N_z upshift generates potential concern for fast-wave current drive if the efficiency scales as N_z^{-2} [12]. The presence of plasma density fluctuations suggests that the required spectral shift may be due to wave scattering from density fluctuations, as described by Andrews and Perkins [10]. In particular, the fast wave was seen only for densities more than a factor of three above the cut-off density calculated for $N_z = 2.2$. This result indicates that lower hybrid fast-wave tokamak experiments should be performed at densities well above the calculated fast-wave cut-off density.

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EXAMINATION OF HEAT TRANSPORT DURING OFF-AXIS NEUTRAL BEAM INJECTION IN DIII-D

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ABSTRACT. Off-axis heating experiments have been conducted in DIII-D using 75 keV neutral beam injection as the auxiliary power source. These H-mode experiments were conducted in a diverted deuterium plasma with values of current $I_p = 0.65$ MA, magnetic field $B_T = 2$ T, density $\langle n_e \rangle = 4.5 \times 10^{19} \text{ m}^{-3}$, aspect ratio $R/a = 1.83/0.48 = 3.8$, and elongation $\kappa = 1.5$. Off-axis heating was accomplished by vertically displacing the plasma by 0.30 m; 85% of the auxiliary heat was deposited outside the normalized minor radius of $\rho = 0.4$. The application of 7.5 MW of deuterium neutral beam power resulted in the plasma transiting into the high density H-mode confinement regime with equal elec-

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tron and ion temperatures. The global thermal energy confinement was not affected by changing the heating location. A power balance analysis employing the 1½-D ONETWO transport code and assuming purely diffusive heat transport found that the one-fluid effective diffusivity changed dramatically between the two cases. These results indicate the possibility that the local diffusivity is a function of some quantity other than the density, temperature and their gradients. An alternative explanation is that the diffusivity remains unchanged and that there is an inward non-diffusive heat flow to balance the power flow.

1. INTRODUCTION

Understanding energy transport remains a primary goal of fusion research [1]. The physical processes that underlie plasma transport in tokamaks are not well understood. The neoclassical plasma transport resulting from Coulomb collisions is less than what is actually determined by power balance analysis. This anomalous transport results in electron thermal diffusivities that