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INTRODUCTION

The theoretical and experimental basis for lower hybrid (LH) current drive (CD) has been well established over the past decade. The same holds for minority ion-cyclotron heating (ICH) by waves in the ion cyclotron range of frequencies (ICRF). In a series of experiments on JET it has been observed that the non-inductive CD efficiency is enhanced when the LHCD waves are used simultaneously with ICH [1]. The theoretical study reported here was motivated by these JET experiments.

In the experiments, the ICRF spectrum, generated by a monopole antenna configuration, is symmetric in $k_\parallel$ and, thus, incapable of generating a net current by itself in a Maxwellian plasma. Consequently, any enhancement in the CD efficiency is due to the interaction of ICRF waves with the asymmetric LHCD electron distribution function. Two aspects of the experimental conditions required for the enhancement play an important role in our studies. First, the excited ICRF spectrum ensures sufficient ICRF power at low values of $k_\parallel$'s. Second, the existence of ion cyclotron and ion-ion hybrid resonaces inside the plasma near the center ensures the existence of a mode conversion layer inside the plasma. Thus, the incident ICRF power, propagated by fast Alfvén waves (FAW), can, in principle, mode convert to ion-Bernstein waves (IBW's). This mode conversion is efficient for small $k_\parallel$'s and for small minority concentrations.

Modeling studies and experiments show that the LH energy and momentum deposition onto the electrons is typically localized and off-center in a tokamak. Since the symmetric ICRF spectrum cannot generate a net current in a Maxwellian plasma, in order to enhance the current drive efficiency ICRF waves have to interact with energetic electrons on the same flux surfaces where LHW's are Landau damped and generate current. Consequently, in our effort to arrive at an understanding of the JET observations, we simplify our analysis to a single flux surface where the LH absorption is a maximum. Since the experimental conditions permit mode conversion, we have studied the effects of both FAW's and IBW's on LH generated energetic electron distribution functions.

In the following we outline our analysis and computations and summarize our principal results. Although the experiments span a wide range of scenarios, we focus on those that pertain to full current drive (i.e. at zero loop voltage) with either LHCD power alone or with LHCD and ICRF powers together.

TWO-DIMENSIONAL VELOCITY SPACE FOKKER-PLANCK STUDIES

The relativistic evolution of the flux surface averaged, and gyro-angle averaged, electron distribution function is given by the Fokker-Planck equation:

$$\frac{\partial}{\partial t}f_o = \frac{\partial}{\partial p_\parallel}D^{LH}\frac{\partial}{\partial p_\parallel}f_o + \frac{\partial}{\partial p_\parallel}D^{FW/IB}\frac{\partial}{\partial p_\parallel}f_o + \left(\frac{\partial}{\partial t}f_o\right)_{collisional} \quad (1)$$

where the D's are the appropriate quasilinear diffusion coefficients [2,3] and $p_\parallel$ is the component of the electron momentum along the magnetic field. In our evaluation of the diffusion coefficient for LHW's, FAW's, and IBW's we make use of the full hot

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Maxwellian plasma dispersion tensor to determine $k_\perp$ and the electric field polarizations. These diffusion coefficients are then used to find the steady-state solution of Eq. (1) using the numerical code CQL3D [4].

For typical JET-type parameters, we find that [2]:

$$\frac{D^{FW}}{D^{LH}} \approx \frac{1}{4}(k_\perp^{FW}\rho_e)^2 \left(\frac{v_\perp}{v_\parallel}\right)^2 \frac{\omega_{LH}}{\omega_{IC}} \ll 1 \tag{2}$$

where ρ_e is the electron Larmor radius, ω_{IC} and ω_{LH} are the ICRF and LH frequencies, respectively. Thus, the FAW diffusion coefficient is very small compared to that of the LHW. On the basis of this comparison, even if the FAW deposited its energy on electrons on the same flux surface as the LHW's, one would not expect the FAW to significantly modify the LH generated electron distribution function in JET. Indeed, numerical solutions of Eq. (1) show this to be the case. Therefore, as a next step, we investigated the effect of mode converted IBW's on LHCD.

An analytical comparison of the IBW diffusion coefficient with the LHW diffusion coefficient has been difficult to obtain since the IBW characteristics near and beyond mode conversion require the use of the full dispersion tensor. In Fig. 1 we show the behavior of the IBW diffusion coefficient as a function of $v_\parallel$ for a series of $v_\perp$'s (for $n_e = 2.4 \times 10^{19}$ m^{-3}, plasma temperature = 6 keV, local magnetic field of 3.3 Tesla, 5% hydrogen minority in a deuterium plasma, and an ICRF frequency of 48 MHz). For the same parameters the lower hybrid diffusion coefficient is: $D_{LH} \approx 0.2 \, (|E_{kz}^{LH}|^2/|E_{ky}^{IB}|^2) \, (\omega_{IC}/\omega_{LH}) \, D_o^{IB}$. In order to study the interaction of IBW's with LHCD generated electron tails two issues, that could seriously limit the efficiency of this interaction, need to be resolved. The first issue has to do with the high (parallel) phase velocities of IBW's at mode conversion. Since low $k_\parallel$'s undergo mode conversion more effectively, a significant portion of the IBW power spectrum is at values of $k_\parallel$ that lie below the LH spectrum. At these values of $k_\parallel$ the IBW's can interact only with the runaway electrons which, at zero loop voltage, do not exist in full LHCD. Furthermore, D_o^{IB} decreases rapidly for IBW phase velocities that are higher than the LHW phase velocities (see Fig. 1). The second issue has to do with the amount of mode converted power to the IBW's. Mode conversion calculations based on [5] show that, for JET-type parameters with a hydrogen minority in a deuterium plasma, less than 25% of the incident FAW power, depending on the minority concentration $\eta = n_H/n_e$, is mode converted to IBW's [2]. However, these problems are satisfactorily aleviated by the dramatic effect of toroidicity on the propagation of IBW's [6]. Both $|k_\parallel|$'s and electric field amplitudes are significantly enhanced along the IBW rays away from mode conversion. The upshifted $k_\parallel$'s allow the IBW's to interact with the energetic electron tails and the stronger electric field increases the diffusion coefficient. The electric field amplitudes can increase by factors ranging from 3 to about 10. The variations in $k_\parallel$'s and electric field amplitudes typically occur over short radial distances of propagation of IBW's [6]. An additional benefit of the toroidal effect on IBW's is that, with the mode conversion layer centrally located in the plasma, $k_\parallel$'s are upshifting as the IBW's propagate towards the flux surface of maximum LHW absorption. By accounting for the increase in the electric field amplitude in the diffusion coefficient, numerical solutions of Eq. (1) show that the IBW's indeed enhance the current drive efficiency.

RESULTS

The Fokker-Planck simulation studies have been done for JET-type parameters. On the flux surface under consideration, we take an electron density n_e of 2×10^{19} m^{-3},

a hydrogen-deuterium plasma with a 3% hydrogen minority, $\nu_{LH} = \omega_{LH}/2\pi = 3.7$ GHz, $\nu_{IC} = \omega_{IC}/2\pi = 48$ MHz, the local toroidal magnetic field of 3.6 Tesla, and the major radius $R = 3$m. The results for the current drive efficiency obtained from the steady-state solution of Eq. (1) are summarized in the following table:

	T_e (keV)	$\overline{D}/D_c$	γ_{cd} ($\times 10^{20}$ A/W m^2)	$T_\perp$ (keV)
LH	1.4	2.0	0.24	25.0
LH + IBW	4.0	2.0 0.1	0.43	27.0

where $\overline{D} = D/D_o$ with D_o as given in [2,3]. The diffusion coefficients are normalized to D_c, the collisional diffusion coefficient, where $D_c = m_e v_{te}\nu_o$ with m_e and $v_{te} = \sqrt{T_e/m_e}$ being the electron mass and thermal velocity, respectively, and ν_o being the electron-electron collision frequency. For LHW's we find the flux-surface averaged $\overline{D}/D_c$ from LHCD simulations, while for IBW's we determine the diffusion coefficient by including the enhancement of the IBW electric field amplitude due to toroidal effects and evaluating $k_\perp$'s and electric field polarizations from the hot Maxwellian plasma dispersion tensor. The current drive efficiency is given by $\gamma_{cd} = n_e RI/P_d$, where I is the current and P_d is the power dissipated. In the case of LHW's only, the lower hybrid spectrum is taken to extend from $3.5v_{te}$ (electron Landau damping limit) to $10.6v_{te}$ (corresponding to the $n_\parallel = 1.8$ of the incident LH spectrum). When ICRF waves are used in typical JET scenarios of LH current drive the bulk electrons and ions are also heated. We take account of this heating by assuming that the temperature of all the species has increased to 4 keV. For this temperature, the LH spectrum extends from $3.5v_{te}$ to $6.3v_{te}$ (corresponding to $n_\parallel = 1.8$) and the IBW spectrum is taken to extend from $v_1^{IB} = 5.7v_{te}$ to very near the speed of light. As seen from the table above, the CD efficiency increases by about 75% in the presence of IBW's. This is comparable to the observed increases in the current drive efficiencies on JET.

The increase in the current drive efficiency is due to a modification, by the IBW's, of the energetic electron tail generated by LHW's. To illustrate this effect we compare, in Fig. 2, the electron parallel distribution function for the case of LH only with the distribution function for LH+IBW with both evaluated at a plasma temperature of 4 keV. The distribution function with LH+IBW is modified sligthly and only beyond that of LH alone at the same electron temperature. This despite the fact that the IBW diffusion coefficient extends further out in $|p_\parallel|$ than the LH spectrum. The reason that the electron tail is not extended to higher momenta is due to the decrease in the IBW diffusion coefficient for higher phase velocities as shown in Fig. 1. Thus, even though the IBW spectrum extends in phase velocity from the region of the LHW spectrum out to near the velocity of light, the electrons are not accelerated from within the LH spectrum to near the velocity of light by IBW's.

In conclusion, we find that an increase in the current drive efficiency with an asymmeteric lower hybrid spectrum lauched into a plasma which is being heated by a symmetric ICRF spectrum can only be explained by the interaction of IBW's with the energetic electron tails generated by LHW's. Smaller minority concetrations and an incident ICRF power spectrum peaked and more concentrated at low values of $k_\parallel$'s would lead to higher CD efficiencies.

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FIGURE 1

FIGURE 2