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ABSTRACT

We determine the conditions for which the interaction of mode converted ion-Bernstein waves (IBW) with the energetic electron tails created by lower hybrid waves (LHW) can lead to an enhancement in the current drive efficiency. This may help explain the "synergy" results obtained on JET.

INTRODUCTION

The study reported here was motivated by JET experiments in which it was observed that the efficiency of LH current drive (CD) was significantly enhanced in the presence of waves in the ion-cyclotron range of frequencies (ICRF) typically used for minority ICR heating.[1] The ICRF spectrum, generated by a monopole antenna configuration, was symmetric in $k_{\|}$ and, thus, incapable of generating a net current by itself. 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 ICRF spectrum, excited in the monopole configuration, ensures sufficient ICRF power at low values of $k_{\|}$'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 $k_{\|}$'s and for small minority concentrations.[2]

Modeling studies and experiments clearly show that the LH energy and momentum deposition onto the electrons is typically localized and off-center. 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. This allows us to isolate the physically relevant mechanisms that are responsible for the enhancement in CD efficiency. Since the experimental conditions permit mode conversion, we study the effect of both FAW's and IBW's on LH generated electron distribution functions.

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:

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

where the D's are the appropriate quasilinear diffusion coefficients and $p_{\|}$ is the component of the electron momentum along the magnetic field. Following the usual procedures,[3] we express the D's in the following convenient forms:

$$D^{LH} = \pi e^2 \sum_{k_{\|}} \left\{ |E_{kz}|^2 \, \delta\left(k_{\|} - \frac{\omega_{LH}}{v_{\|}}\right) \; D_o^{LH} \right\} \tag{2a}$$

$$D^{FW/IB} = \pi e^2 \sum_{k_{\|}} \left\{ |E_{ky}|^2 \, \delta\left(k_{\|} - \frac{\omega_{IC}}{v_{\|}}\right) \; D_o^{FW/IB} \right\} \tag{2b}$$

where

$$D_o^{LH} = \frac{1}{|v_{\|}|} \left[\left\{ J_0 - \frac{v_\perp}{v_{\|}} J_1 \mathrm{Im}\left(\frac{E_{ky}}{E_{kz}}\right)\right\}^2 + \left\{ \frac{v_\perp}{v_{\|}} J_1 \mathrm{Re}\left(\frac{E_{ky}}{E_{kz}}\right)\right\}^2 \right] \tag{3a}$$

$$D_o^{FW/IB} = \frac{1}{|v_{\|}|} \left[\left\{ \frac{v_\perp}{v_{\|}} J_1 + J_0 \mathrm{Im}\left(\frac{E_{kz}}{E_{ky}}\right)\right\}^2 + \left\{ J_0 \mathrm{Re}\left(\frac{E_{kz}}{E_{ky}}\right)\right\}^2 \right] \tag{3b}$$

ω_{LH} and ω_{IC} are the frequencies of the LHW's and ICRF waves, respectively, J_0 and J_1 are Bessel functions with argument $k_\perp v_\perp/\omega_{ce}$, the electric field $\vec{E} = \sum \vec{E}_k \cos\left(k_\perp x + k_{\|} z - \omega t\right)$ with the sum extending over the range of $k_{\|}$'s excited for each wave, and $k_\perp$ as well as the polarizations being determined from the full hot Maxwellian plasma dispersion tensor. The purpose of expressing the diffusion coefficients in different forms for the LHW's and FAW/IBW's is that, while the expression in Eqs. (3a,3b) depend only on the local plasma properties and electric field polarizations, the electric field amplitudes multiplying D_o in Eqs. (2a,2b) can be related to the incident power density, for the appropriate waves.[4] These diffusion coefficients are then used to find the steady-state solution of Eq. (1) using the numerical code CQL3D.[5]

For typical JET-type parameters, we find from Eqs. (2a,2b,3a,3b):

$$\frac{D^{FW}}{D^{LH}} = \frac{\left|E_{ky}^{FW}\right|^2 D_o^{FW} \delta\left(k_{\|} - \frac{\omega_{IC}}{v_{\|}}\right)}{\left|E_{kz}^{LH}\right|^2 D_o^{LH} \delta\left(k_{\|} - \frac{\omega_{LH}}{v_{\|}}\right)} \approx \frac{1}{4}(k_\perp^{FW} \rho_e)^2 \left(\frac{v_\perp}{v_{\|}}\right)^2 \frac{\omega_{LH}}{\omega_{IC}} << 1 \tag{4}$$

where ρ_e is the electron Larmor radius, and we have taken $\left|E_{ky}^{FW}\right| \sim \left|E_{kz}^{LH}\right|$, i.e. 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 investigate the effect of mode converted IBW's on LHCD.

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, the IBW $k_{\parallel}$-spectrum lies below the LH spectrum. Thus, at mode conversion IBW's could only act on runaway electrons which, at zero loop voltage, do not exist in full LHCD. The second issue has to do with the amount of mode converted power to the IBW's. Mode conversion calculations [2] 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:

Table I Mode conversion coefficient C versus η for $k_{\parallel} = 1\ \text{m}^{-1}$

η	0.1	0.05	0.03	0.01
C(%)	0.1	2.5	12	25

However, both of these problems are satisfactorily resolved 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

Our numerical examples are for JET-type parameters. On the flux surface under consideration, we take an electron density n_e of $2 \times 10^{19}\ \text{m}^{-3}$, a hydrogen-deuterium plasma with a 3% hydorgen 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 are summarized in the following table:

Table II

	T_e (keV)	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		2.0		
+	4.0		0.43	27.0
IBW		0.1		

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} 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 D/D_c from LHCD simulations, while for IBW's we determine the diffusion coefficient by combining all the information discussed above. 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 $5.7v_{te}$ 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.

In conclusion, our studies show that an increase in the current drive efficiency is likely to occur when IBW's interact with the energetic electron tails. The effect of FAW's on LH current drive efficiency is negligible.

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REFERENCES

1. C. Gormezano, M. Brusati, A. Ekedahl, P. Froissard, J. Jacquinot, and F. Rimini, Proceedings of the IAEA Technical Meeting on Fast Wave Current in Reactor Scale Tokamaks (Synergy and Complementarity with LHCD and ECRH), Arles, France, September 23-25, 1991. Eds. D. Moreau, A. Bécoulet, and Y. Peysson, p. 244.
2. V. Fuchs and A. Bers, Phys. Fluids 31, 3702 (1988).
3. C.F. Kennel and F. Engelmann, Phys. Fluids, 9, 2377 (1966); I. Lerche, Phys. Fluids, 11, 1720 (1968).
4. A. Bers, Plasma Physics – Les Houches 1972, Eds. C. DeWitt and J. Peyraud (Gordon and Breach, N.Y., 1975), p. 113.
5. M.G. McCoy, G.D. Kerbel, R.W. Harvey, AIP Conf. Proc. 159, 77 (1987); R.W. Harvey, M.G. McCoy, G.D. Kerbel, AIP Conf. Proc. 159, 49 (1987).
6. A.K. Ram and A. Bers, Phys. Fluids B3, 1059 (1991).