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* *See Appendix 1*

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Transport and Gyrokinetic Effects on Heating and Current Drive in Tokamaks

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Introduction

Accurate interpretation of heating and current drive experiments in the electron and ion cyclotron ranges of frequencies requires inclusion of the influences of both plasma transport processes and wave propagation and absorption. These issues are addressed in this paper using a three dimensional electron Fokker-Planck code and gyrokinetic theory respectively.

Transport Effects

The use of Lower Hybrid heating (LH) and Electron Cyclotron Resonance Heating (ECRH) to drive currents in tokamaks has received much attention. These schemes have been proposed for both bulk current drive to reduce Volt-second requirements and localised control of the current density profile to improve MHD stability. However it has been recognised that radial transport of particles can both reduce the overall current drive efficiency and broaden the driven current profile [1, 2, 3]. We give results from a numerical solution of the electron Fokker-Planck equation which, for the first time, gives a self-consistent solution for the electron distribution function in all three co-ordinates: speed, pitch angle and flux surface radius. The Fokker-Planck equation solved includes all the most relevant features of these current drive processes: electron-electron and electron-ion collisions, electron trapping through bounce-averaging of the equation, relativistic effects, and quasilinear diffusion terms to model the heating. The radial transport is modelled by both pinch and diffusion terms.

The increase in plasma resistance due to radial transport processes in Ohmically heated tokamaks in which the collision and confinement times are comparable is assessed, and can be greater than that due to neoclassical effects. Results are presented which demonstrate that this increase might account for the anomalously high resistance observed in pinches and some tokamaks. In the CLEO ECRH current drive experiments [4] the efficiency was one third of that predicted theoretically. We show that this reduced efficiency is consistent with the diffusivity of the heated electrons, assumed similar to the thermal diffusivity of the plasma, being comparable with a^2/τ with a the minor radius and τ the collision time of the heated electrons.

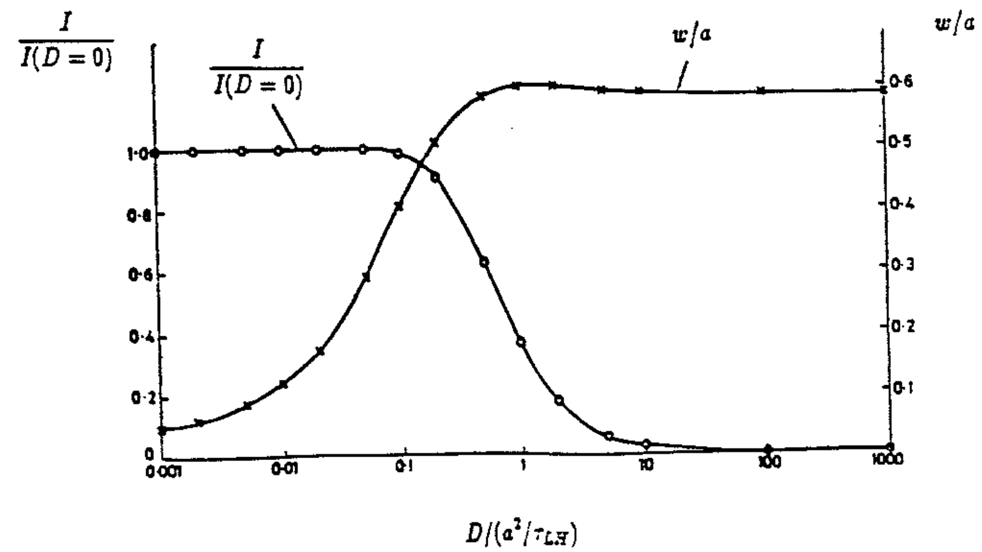

Figure 1

The effect of radial transport on LH current drive profiles is also studied. Figure 1 shows the effect of transport on both the LH driven current I and the width of the current profile w normalised to a. The power deposition is Gaussian, centred at $r = a/2$ and on electrons with $v_\parallel = 3(2T_e/m_e)^{1/2}$, with widths $\Delta r = 0.05a$ and $\Delta v_\parallel = 0.1 \times (2T_e/m_e)^{1/2}$. For simplicity Figure 1 shows results for flat temperature and density profiles, but the conclusions are similar for more realistic profiles. No pinch term is included in the transport for Figure 1 and D, the diffusion coefficient of the heated electrons, is normalised to a^2/τ_{LH} with τ_{LH} the collision time of the heated electrons ($\simeq 0.05E^{3/2}/n$ msecs, with E their energy in keV and n the density in 10^{19} m^{-3}). Transport can lead to a broadening of the current profile even in large machines, an effect which should be included when considering the use of these schemes to control localised MHD modes in current and future devices such as JET and ITER.

Gyrokinetic effects

In the ion cyclotron range of frequencies, gyrokinetic theory [5] is used to calculate the total absorption and power deposition profiles resulting from fast wave heating in a tokamak plasma. This theory has been developed to take account of the effect of the variation of the equilibrium magnetic field across the Larmor orbit of a particle in cyclotron resonance. In principle, this effect may be included to all orders subject only to the constraint $k_\perp \rho \ll L/\rho$ where L is the scale length of the equilibrium, ρ the Larmor radius and $k_\perp$ the perpendicular wave number. In contrast to much previous work, gyrokinetic theory yields a self-consistent local dispersion relation because the particle response includes the effect of the non-uniform equilibrium magnetic field. This feature introduces a new perpendicular dissipation resonance broadening mechanism.

Specific results are obtained for a model configuration whose parameters are appropriate to JET. First, we present calculations of total minority ion cyclotron absorption and the power deposition profile obtained from the self-consistent local dispersion relation. This approximation is expected to be reliable when reflection from the hybrid cut-off is negligible, corresponding to large values of the parallel wave number and minority ion densities $\lesssim 10\%$. The local analytical model permits rapid computation of the absorbed power and the power deposition profile as a function of the majority and minority ion densities, the magnetic field, the minority ion temperature and the scale length L_B of the equilibrium magnetic field. It also includes the effect of three dimensional wave fields through the wave numbers $k_x(x)$, k_y and k_z where x is the direction of the field gradient, and yields information previously obtainable only from numerical full wave treatments.

In addition we present results on the new perpendicular ion cyclotron damping mechanism mentioned above. It is found that this damping is only significant below a certain minority to majority density ratio which is proportional to ρ_b/L_B where ρ_b is the minority ion Larmor radius. For minority densities below this value, the hybrid resonance does not occur and perpendicular damping takes place. For minority densities larger than the critical value, the hybrid resonance occurs with the result that the right circularly polarised component of the electric field is reduced almost to zero in the minority resonance region, and there is no damping. The results suggest that the perpendicular damping is proportional to v_{Tb}/c_A the ratio of minority thermal speed to Alfven speed. Strong perpendicular damping is therefore expected when $v_{Tb} \geq c_A$ which corresponds to $k_\perp \rho_b \geq 1$. In order to investigate this regime relevant to fusion products and ICRF-generated ion tails, the analysis must be extended to include $k_\perp \rho_b \geq 1$.

For cases where reflection (for low-field-side incidence) is significant, we have extended the local gyrokinetic treatment to a full wave description which gives the reflection, transmission and absorption coefficients. In this case, the absorption is the sum of the power dissipated by minority ions and the power mode-converted to the ion Bernstein wave. We are extending the analysis to include the case $k_\perp \rho_b \gtrsim 1$, relevant to hot ions, and separating the power dissipated from the mode-converted power.

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APPENDIX 1.

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