Combined RF Current Drive and Bootstrap Current in Tokamaks[1]

S.D. Schultz, A. Bers, and A.K. Ram

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Abstract. By calculating radio frequency current drive (RFCD) and the bootstrap current in a consistent kinetic manner, we find synergistic effects in the total non-inductive current density in tokamaks [1]. We include quasilinear diffusion in the Drift Kinetic Equation (DKE) in order to generalize neoclassical theory to highly non-Maxwellian electron distributions due to RFCD. The parallel plasma current is evaluated numerically with the help of the FASTFP Fokker-Planck code [2]. Current drive efficiency is found to be significantly affected by neoclassical effects, even in cases where only circulating electrons interact with the waves. Predictions of the current drive efficiency are made for lower hybrid and electron cyclotron wave current drive scenarios in the presence of bootstrap current.

INTRODUCTION

We perform full kinetic calculations of the plasma current density in a tokamak, including both radial drifts, which lead to the bootstrap current, and radio frequency current drive (RFCD). By including both effects it is possible to find synergistic interactions.

EXPANSION OF DRIFT KINETIC EQUATION

The electron current density is calculated as $J_\| = -e\int d^3p\, v_\| f$ where the electron distribution function f is a function of momentum $\mathbf{p}$ for relativistic electrons, and $v_\| = p_\|/\gamma m$, with γ the relativistic factor $\sqrt{1+p^2/m^2c^2}$. We take f to be at steady state, gyroaveraged, and independent of the toroidal angle ζ.Under these assumptions, f is a function of the guiding center coordinates r and θ and two constants of the motion, the electron's energy E and magnetic moment μ. Then f satisfies the *drift kinetic equation* (DKE)

$$v_\| \frac{B_\theta}{B}\frac{1}{r}\frac{\partial f}{\partial \theta} + v_{Dr}\frac{\partial f}{\partial r} = C(f) + Q(f). \tag{1}$$

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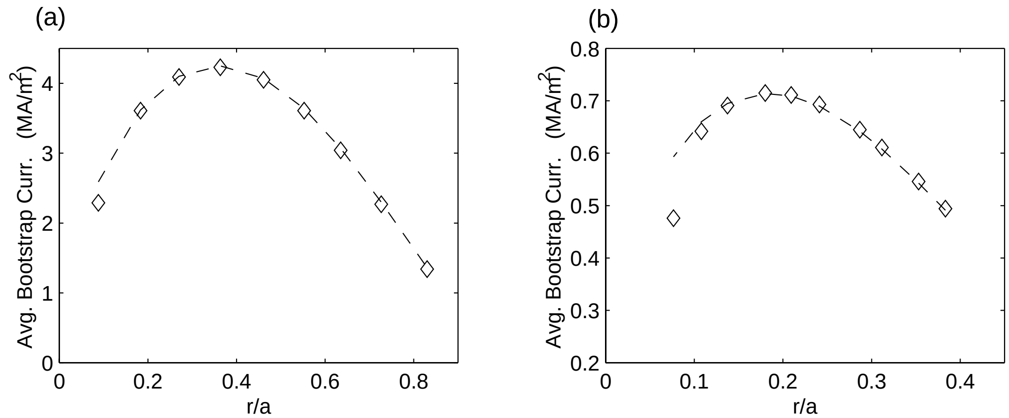

FIGURE 1. Bootstrap current as a function of r/a, from FASTFP-NC (diamonds) and Ref. [5] (dashed line), for (a) Alcator C-Mod high-β parameters ($R_0 = 0.65m$, $a = 0.22m$, $B_0 = 4T$, $n_0 = 2.5 \times 10^{20} m^{-3}$, $T_{e0} = 7.5keV$, $T_{i0} = 1.0keV$) and (b) DIII-D ($R_0 = 2.62m$, $a = 0.95m$, $B_0 = 2T$, $n_0 = 4.3 \times 10^{19} m^{-3}$, $T_{e0} = 7.8keV$, $T_{i0} = 6.2keV$)

where $C(f)$ is a collision operator, $Q(f)$ is the quasilinear operator for diffusion due to RF waves, and v_{Dr} is the radial drift due to magnetic field gradient and curvature.

In previous works [1] we described the expansion of (1) in the small parameter $\delta = \tau_{t,b}/\tau_D$, where $\tau_{t,b}$ is the electron's transit or bounce time, and τ_D is a typical time for radial drift of the electron. The result, in analogy with standard neoclassical theory [3,4], is $f = f_0 + \delta f_1 = f_0 + \tilde{f} + g$,where

$$\{C(f_0)\} + \{Q(f_0)\} = 0 \tag{2}$$

$$\tilde{f} = -\frac{v_\parallel}{\Omega_\theta}\frac{\partial f_0}{\partial r} \tag{3}$$

$$\{C(g)\} + \{Q(g)\} = -\left\{C(\tilde{f})\right\} - \left\{Q(\tilde{f})\right\} \tag{4}$$

where the braces $\{...\}$ denote bounce averaging, removing the θ dependence by integrating over the orbit of the electron.

THE FASTFP-NC CODE

To accurately solve the complicated set of equations (2-4), numerical methods and computers provide the best approach. The FASTFP-NC code solves these equations and calculates the current density by numerically integrating $J_\parallel$. It incorporates the FASTFP Fokker-Planck code [2], written by M. Shoucri and I. Shkarofsky, to solve the Fokker-Planck equation (2). The remainder of the code

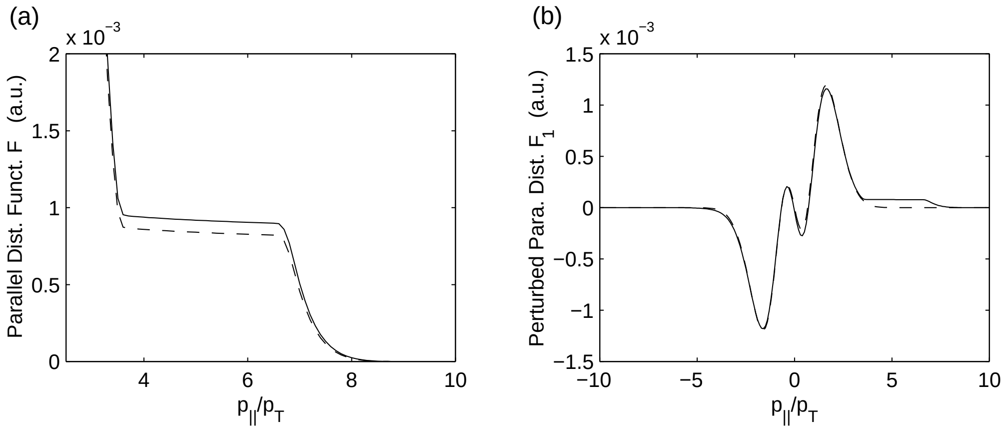

FIGURE 2. Parallel distribution function for LHCD as a function of $p_\parallel/p_{Te}$: (a)$F = \int 2\pi p_\perp f dp_\perp$ with RF only (dashed line) and RF plus radial drifts (solid line), (b)$F_1 = \int 2\pi p_\perp(\tilde{f} + g)dp_\perp$ for bootstrap alone (dashed line) and bootstrap with RF (solid line). Parameters are for Alcator C-Mod type plasma (see Fig.1).

uses imposed density and temperature profiles (which are assumed not to change on the timescales of interest) to evaluate $\tilde{f}$ in (3), calculates the "source term" $-\{C(\tilde{f})\} - \{Q(\tilde{f})\}$ in (4), calculates g from (4), then performs the integral to get the current density.

Early benchmarking of FASTFP-NC shows that the bootstrap current can be calculated accurately in the absence of RF waves, in comparison to theory [5]. Figure 1 shows FASTFP-NC calculations (denoted with a diamond) and theory (the dashed line), which agree except at small values of r.

LHCD AND THE BOOTSTRAP CURRENT

We consider off-axis lower hybrid current drive (LHCD) with Alcator C-Mod parameters. (r=0.15m, ϵ=0.23) The quasilinear operator Q is taken to be

$$Q(f) = \frac{\partial}{\partial p_\parallel} D \frac{\partial f}{\partial p_\parallel}; \qquad \frac{D}{\nu_e p_{Te}^2} = 4.0; \qquad 3.5v_{Te} < v_\parallel < 6v_{Te}$$

The RF driven current density with no radial drifts was found by FASTFP to be 10.48 MA/m^2. The bootstrap current density with no RF is 2.71 MA/m^2. The total current density found with FASTFP-NC is greater than their sum by 0.35 MA/m^2. However, the current drive figure of merit, found by taking $(J_\parallel - J_{BS})/P_{abs}$, is unchanged by including radial drifts in RFCD calculations.

Figure 2 shows the parallel distribution function from FASTFP-NC compared to cases with RF only and bootstrap current only. We observe that the current density has increased due to an increase in the height of the LH plateau. From

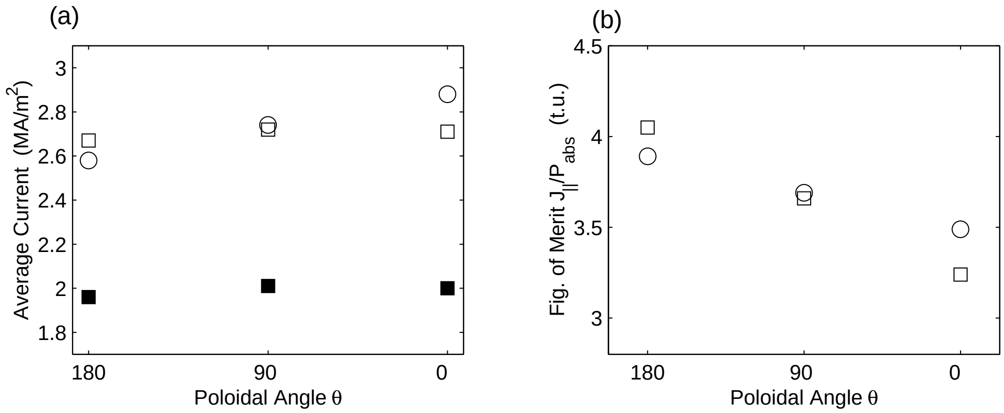

FIGURE 3. Electron cyclotron current drive with DIII-D parameters (see Fig.1): (a) Flux-surface-averaged current density as a function of poloidal angle of RF deposition: RFCD only (solid square); RFCD plus bootstrap current, calculated separately (open square); and RF and bootstrap current density calculated together, from FASTFP-NC (circle). (b) Current drive figure of merit with RFCD only (square) and RF with radial drifts from FASTFP-NC (circle).

standard neoclassical theory (the dashed line in Figure 2b), we can estimate that the RF-driven current will increase by a factor of $A\sqrt{\epsilon}(\rho_\theta/L_T)(v_1/v_{Te})^3$, where A is of order one, ρ_θ is the poloidal gyroradius, L_T is the scale length of the temperature gradient, and v_1 is the lower limit in phase velocity of the spectrum of lower hybrid waves.

ECCD AND THE BOOTSTRAP CURRENT

We show off-axis electron cyclotron current drive (ECCD) with DIII-D parameters (r=0.2m, ϵ=0.08) in Figure 3. It can be seen that there is an interaction between the RF driven current and the bootstrap current which depends on the poloidal angle at which the RF power is deposited by Doppler-shifted cyclotron damping. The figure of merit $(J_\parallel - J_{BS})/P_{abs}$ also is affected by the synergism. Further details are given in the caption to Figure 3.

REFERENCES

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