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On Synergism between Bootstrap and Radio-Frequency Driven Currents

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Introduction

In advanced scenarios of steady-state operation in tokamaks, radio-frequency (RF) driven currents have to be calculated self-consistently with the bootstrap current (BC). This is addressed for the case of lower hybrid (LH) and electron cyclotron (EC) current drive.

Kinetic description [1]

A self-consistent description, for axisymmetric plasmas, of the RF driven current with the effect of radial drifts due to the magnetic field gradient and curvature is obtained from the steady-state drift-kinetic equation (DKE)

$$\frac{v_\theta}{r}\frac{\partial f}{\partial \theta} + v_{Dr}\frac{\partial f}{\partial r} = C(f) + Q(f) \; ; \tag{1}$$

where f is the electron distribution function, (r, θ) are the radial and poloidal positions, v_θ is the velocity along the poloidal field lines and v_{Dr} is the drift velocity across the field lines. The effects of collisions and RF driven quasilinear diffusion are described, respectively, by the operators $C(f)$ [2] and $Q(f)$ [3]. The distribution function is expanded as $f \approx f_0 + \delta f_1 = f_0 + \tilde{f} + g$ where the expansion parameter is $\delta = v_{Dr}/v_\theta$. Here f_0 is the RF-generated distribution unperturbed by radial drifts and given by the usual bounce-averaged Fokker-Planck (FP) equation in the absence of BC. $\tilde{f}$ is the perturbation due to radial drifts and gradients, and g is the response of the plasma due to collisions and RF fields. In the low-collisionality regime, the collisional detrapping time τ_{dt} is much longer than the bounce time τ_b of trapped electrons, so that a sub-ordering $\delta \ll \tau_b/\tau_{dt} \ll 1$ can be used to further expand and solve (1) as in [1]:

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

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

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

where $\{\mathcal{A}\}$ denotes the bounce-averaging operation, $v_\parallel$ is the particle velocity along the field line, and Ω_θ is the poloidal gyrofrequency.

The system (2)-(4) is solved in the small inverse aspect ratio approximation $\epsilon = r/R_0 \ll 1$, using the 3-D, bounce-averaged, relativistic, quasilinear Fokker-Planck code *dkeyp* that calculates the steady-state distribution function f in momentum space at the radial position r. Details of the numerical schemes in *dkeyp* and its novel treatment of the trapped-passing boundary in momentum space are in [4].

In order to evaluate the interaction between RF driven currents and the bootstrap current, the following flux surface averaged quantities are computed: J^{RF} and P^{RF}, which are, respectively, the RF current density and the density of power absorbed, in the absence of bootstrap current; J^{B}, the BC density in the absence of RF; J and P, which are, respectively, the self-consistent total current density and the total density of power absorbed. The synergistic current density is given by $J^{\mathrm{S}} = J - (J^{\mathrm{RF}} + J^{\mathrm{B}})$, and the internal figure of merit for the current drive is given by $\eta = (J - J^{\mathrm{B}})/P$. This is compared with $J^{\mathrm{RF}}/P^{\mathrm{RF}} = \eta^{\mathrm{RF}}$.

Self-consistent calculation of LHCD and BC

The self-consistent calculation of LHCD with the BC was carried out using the parameters from the proposed scenario for Alcator C-Mod [5] where LHCD at $r/a = 0.7$ will supplement the large bootstrap fraction of the current. A simplified LH power spectrum is assumed to be constant in $k_{\|}$ between two limits fixed by accessibility and by strong linear Landau damping conditions. The normalized LH quasilinear diffusion coefficient chosen in our calculation is $D_0^{\mathrm{LH}} = 1.0\ \nu_e p_{Te}^2$, which corresponds to an incoming LH power of $P^{\mathrm{LH}} = 2$ MW. A parametric study of the synergism shows that the synergistic current increases linearly with the part of the BC generated by temperature gradients, but is independent of density gradients, confirming the analytical prediction obtained in the Lorentz limit $Z_i \gg 1$ in [1]:

$$\frac{J_{\|}^{(S)}}{J_{\|}^{(LH)}} \approx \frac{1}{2}\sqrt{\epsilon}\rho_\theta \frac{d\ln T_e}{dr}\left(\frac{p_{\|\min}}{p_{Te}}\right)^3 \tag{5}$$

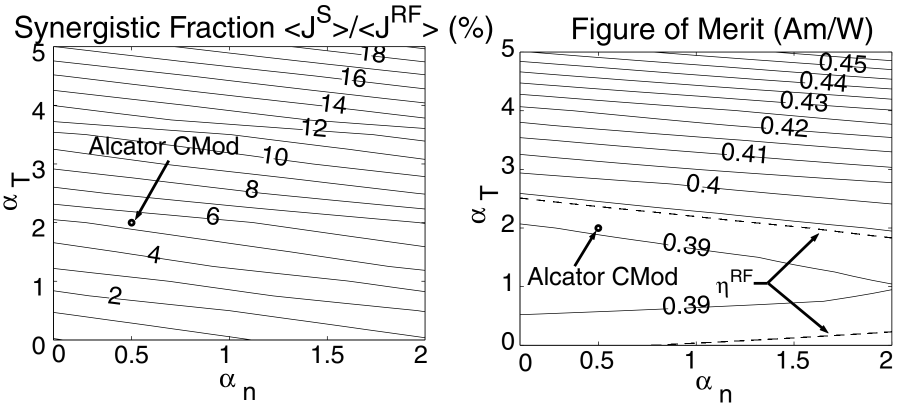

Figure 1:

Typically $p_{\parallel\min}/p_{Te} \approx 3.5$. In Fig. 1 are shown contour plots of the synergistic fraction of the current J^S/J^{LH}, and of the figure of merit η, for various temperature and density gradients $[T_e \sim (1-(r/a)^2)^{\alpha_T},\ n_e \sim (1-(r/a)^2)^{\alpha_n}]$. If the temperature gradient at $r/a = 0.7$ in Alcator C-Mod were made twice as steep, the BC would increase by 80% and the synergistic fraction would increase from 5% to 12% of the LH driven current; Correspondingly, there is an 8% increase in the figure of merit. Therefore, large temperature gradients could result in a significant increase in the synergistic effect between LHCD and BC.

Self-consistent calculation of ECCD and BC

Current drive by second harmonic X-Mode excitation is considered, assuming a Gaussian power spectrum centered around $N_{\parallel 0}$ with a width $\Delta N_{\parallel} = 0.02$. The maximum value of the EC diffusion coefficient for an incoming power of 10 MW is $D_0^{\mathrm{EC}} = 0.14\ \nu_e p_{Te}^2$. ECCD is illustrated for Alcator C-Mod parameters (although ECCD is not planned in C-Mod at this time) for low-field side (LFS) absorption. ECCD far off axis $(r/a = 0.7)$ on the LFS is known to lead to poor CD efficiency due to the Ohkawa effect generated by a large number of trapped electrons. However, it is possible to use the Ohkawa current in a positive way, by launching waves with $N_\parallel < 0$, and adjusting the wave parameters so that the EC diffusion region in velocity space is located just below the trapped-passing boundary. Electrons are then mostly diffused into the trapped region and the Ohkawa effect becomes dominant. This is referred as the Ohkawa method for ECCD, and here noted as OKCD. The wave parameters $N_\parallel$ and $2\omega_{ce}/\omega$ determine the location of the EC diffusion region in momentum space, and can be varied so as to optimize the current driven by either ECCD ($N_\parallel = 0.28$, $2\omega_{ce}/\omega = 0.97$) or OKCD ($N_\parallel = -0.30$, $2\omega_{ce}/\omega = 0.98$). The self-consistent calculation of ECCD with BC is performed using these optimized parameters and the results are presented in Table 1.

ECCD	EC	EC + Syn
$\langle J_\parallel \rangle$ (MA/m^2)	0.49	0.62
$\langle P_{\mathrm{abs}} \rangle$ (MW/m^3)	22.1	22.6
η (Am/W)	0.022	0.028

OKCD	OK	OK + Syn
$\langle J_\parallel \rangle$ (MA/m^2)	12.37	12.96
$\langle P_{\mathrm{abs}} \rangle$ (MW/m^3)	278.8	276.3
η (Am/W)	0.044	0.047

Table 1:

First, it can be observed that a much larger current density is obtained for OKCD than for ECCD. In addition, the figure of merit is better, thus making OKCD more desirable than ECCD for off-axis CD on the LFS. A synergism is found both for ECCD and for OKCD, although the synergistic fraction of the current is much larger for ECCD (28%) than for OKCD (5%). In contrast to LHCD, synergism is also obtained in the figure of merit (25% increase in η for ECCD, and 5% for OKCD). The physical mechanism of the synergism between ECCD or OKCD and the bootstrap current can be visualized in a 2-D contour plot of the perturbed distribution $\delta f_1 = \tilde{f} + g$ generated by the radial drifts, displayed in Fig. 2 with (dashed lines) and without (solid lines) ECCD (a) or OKCD (b). In the case of ECCD, the synergism can be simply interpreted as the Fisch-Boozer effect on the 'bootstrap' distribution. The Ohkawa effect on f_1 is however different from f_0 because f_1 is mostly negative for $p_{\|} < 0$. Indeed, the synergism between OKCD and BC is a competition between a negative effect of EC-induced electron trapping where $f_1 < 0$ and $p_{\|} < 0$, and a positive effect due the asymmetry in f_1, which leads to an increase in f_1 where $p_{\|} > 0$.

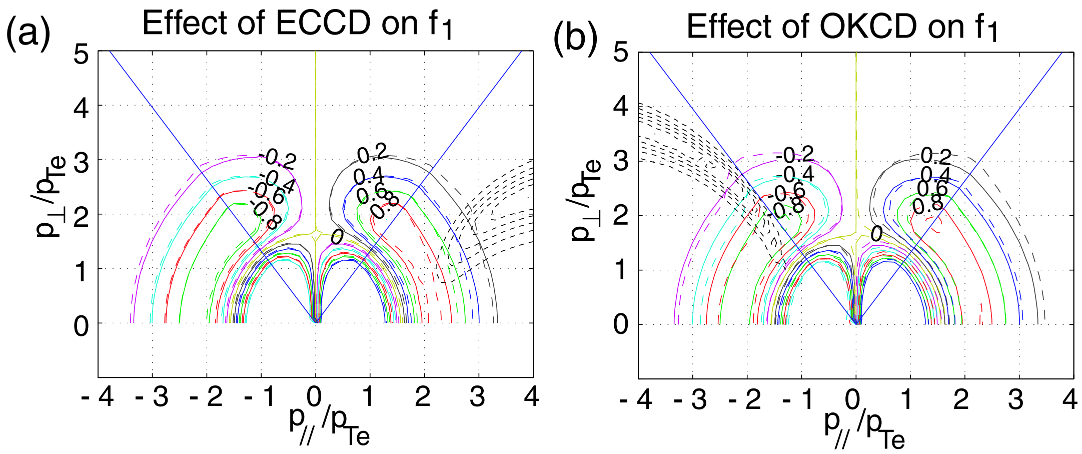

Figure 2:

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