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Introduction

In high temperature tokamak confined plasmas, electron cyclotron current drive (ECCD) [1] entails a competition between current drive by the Ohkawa mechanism (OKM) [2] and the Fisch-Boozer mechanism (FBM) [3]. We have shown recently [4][5] that the OKM of current drive (OKCD) is more suitable for effectively generating significant current at positions off the magnetic axis, on the outboard low field side (LFS), of interest to various advanced tokamak operation scenarios, and STs, requiring current profile control. At such positions the bootstrap current (BC) is also appreciable and OKCD must be evaluated self-consistently in the presence of BC; we present results from such a self-consistent formulation and evaluate the synergism between OKCD and BC.

Description of Kinetic Model and Computations

The kinetic formulation and initial computational results were given in [4] following [6]. Considering an axisymmetric toroidal plasma geometry with circular concentric flux-surfaces, OKCD and BC are self-consistently described by 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 $f = f\left(r, \theta, p_\parallel, p_\perp\right)$ is the electron distribution function, (r, θ) are the radial and poloidal positions, $(p_\parallel, p_\perp)$ are the components of the momentum, respectively, parallel and perpendicular to the magnetic field, v_θ is the velocity along the poloidal field lines and v_{Dr} is the drift velocity across the field lines due to the magnetic field gradient and curvature. The effects of collisions and RF driven quasilinear diffusion are described, respectively, by the operators $C(f)$ [7] and $Q(f)$ [8]. The DKE is expanded in the small drift approximation [6] and solved by the code *DKE* [9] which gives the steady-state distribution function (DF) f. To determine the synergism in OKCD with BC, we let $f = f^{\mathrm{OK}} + f^{\mathrm{BC}} + f^{\mathrm{S}}$, where f^{OK} is the DF due to electron cyclotron waves (ECWs) when the BC is neglected, f^{BC} is the DF giving the BC in absence of ECWs, and f^{S}, giving additional current, can then be taken as the synergistic DF. Flux surface averaged $v_{\parallel}$-moments of these DFs give the OKCD current density $\left\langle J^{\mathrm{OK}}\right\rangle$ when the BC is neglected, the BC density $\left\langle J^{\mathrm{BC}}\right\rangle$ in the absence of ECWs, and the synergistic current density $\left\langle J^{\mathrm{S}}\right\rangle$. The density of power absorbed in OKCD is calculated with $\left(\left\langle p_d^{\mathrm{TOT}}\right\rangle\right)$ and without $\left(\left\langle p_d^{\mathrm{OK}}\right\rangle\right)$ the effect of radial drifts. The intrinsic figure of merit is then computed including $\left(\eta = \left[\left\langle J^{\mathrm{OK}}\right\rangle + \left\langle J^{\mathrm{S}}\right\rangle\right] / \left\langle p_d^{\mathrm{TOT}}\right\rangle\right)$, or not including $\left(\eta^{\mathrm{OK}} = \left\langle J^{\mathrm{OK}}\right\rangle / \left\langle p_d^{\mathrm{OK}}\right\rangle\right)$, the synergistic effects.

Calculations were carried out for advanced tokamak plasma parameters typical of JT-60[10] with major radius $R = 3.35$ m, minor radius $a = 0.8$ m, magnetic field on axis $B_t = 3.4$ T. The following profiles were taken: electron temperature $T_e\left(\rho \equiv r/a\right) = 4.7\left(1-\rho^2\right)^{1.55} + 1.5$ keV, ion temperature $T_i\left(\rho\right) = 7.0\left(1-\rho^2\right) + 0.6$ keV, electron density $n_e\left(\rho\right) = \left[3.55\left(1-\rho^2\right)^{1.5} + 0.25\right] \times 10^{19}$ m^{-3}. A uniform effective ion charge $Z_{\mathrm{eff}} = 3$ was used. The ECW power was considered to be in a Gaussian beam of width 2 cm, polarized in the quasi-X mode. The wave-particle interaction occurred near the second harmonic of the electron cyclotron frequency, $\omega \simeq 2\Omega_{\mathrm{ce}}$. The beam was assumed to be launched horizontally in the mid-plane from the LFS.

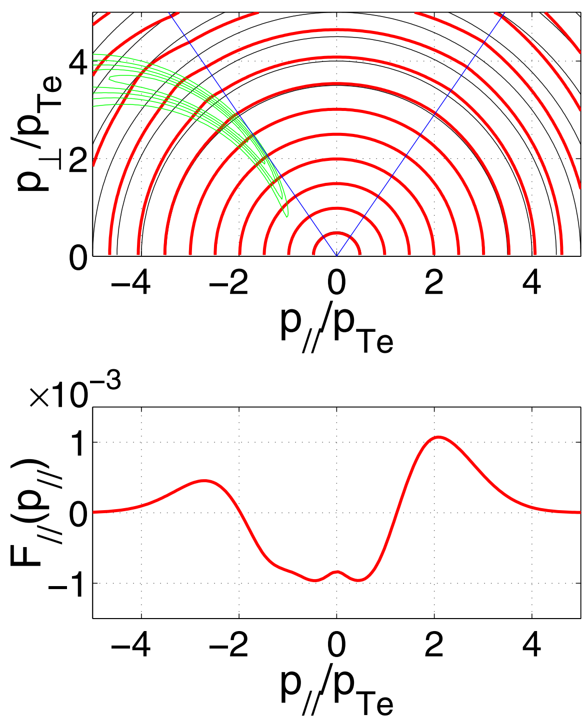

Figure 1: f^{OK} (a) and $F_{\parallel}^{\mathrm{OK}}$ (b)

The resonant electrons are selected according to the resonance condition, which can be written as $\gamma - N_{\parallel}\left(p_{\parallel}/mc\right) - 2\Omega_{ce}/\omega = 0$ where $\gamma \equiv \left[1 + \left(p_{\parallel}^2 + p_{\perp}^2\right)/m^2c^2\right]^{1/2}$ is the relativistic factor, and $N_{\parallel} \equiv k_{\parallel}c/\omega$ is the parallel index of refraction. Across the resonance region, $N_{\parallel}$ remains approximately constant, and the resonance curve in momentum space depends mostly upon the variations of the ratio $2\Omega_{ce}/\omega$. For $N_\parallel = -0.3$, the power absorption profile is centered about a radial location $\rho = 0.8$ by setting the wave frequency such that $2\Omega_{ce}/\omega = 0.983$. OKCD is calculated with these parameters and an incident energy flow density $S_{\text{inc}} = 12$ kW/m^2 on the flux-surface, which corresponds to an EC beam of total power 1 MW.

OKCD in Absence of Bootstrap Current

The 2-D DF f^{OK} is shown on Fig. 1 (a). The ECW diffusion coefficient (dashed lines) in momentum space is located on the counter-passing side for OKCD, and right under the trapped/passing boundary, so that trapping is induced as electrons gain perpendicular momentum from the wave. Because of the fast bounce motion, the distribution function is symmetrized in the trapped region in a time much shorter than the detrapping time. As a consequence, detrapping occurs symmetrically on the co- and the counter-passing sides.

An asymmetric trapping on the counter-passing side with a symmetric detrapping results in a accumulation of electrons on the co-passing side. This effect is evident when the distribution function is integrated over the perpendicular momentum as

$$F_\parallel^{\text{OK}} = 2\pi \int_0^\infty dp_\perp \, p_\perp \left(f^{\text{OK}} - f_M \right) \quad (2)$$

as shown in Fig. 1 (b). The OKM current is generated by the accumulation of electrons with a positive $p_\parallel$, which clearly dominates the FBM current related to electrons with a negative $p_\parallel$. The OKCD current density is found to be $\langle J^{\text{OK}} \rangle = 109$ kA/m^2, and the density of power absorbed is found to be $\langle p_d^{\text{OK}} \rangle = 261$ kW/m^3. The resulting figure of merit is $\eta^{\text{OK}} = 0.42$ A·m/W.

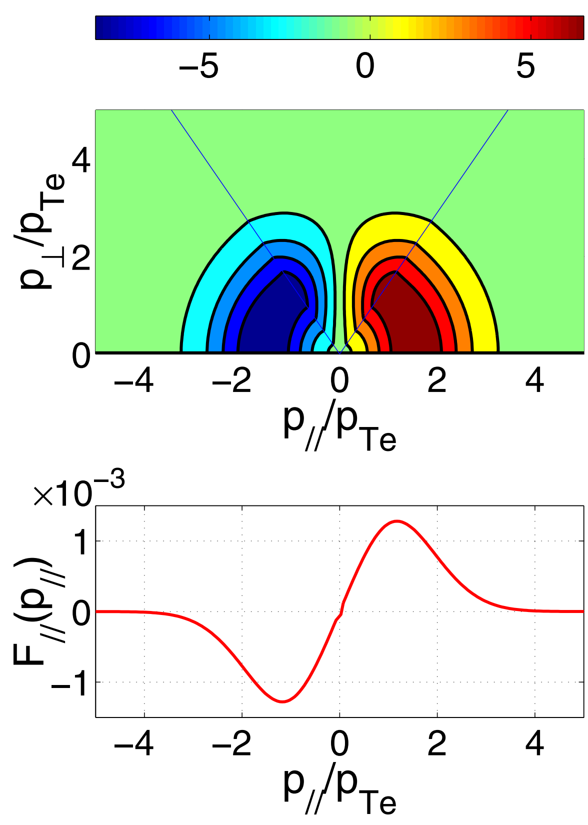

Figure 2: f^{BC} (a) and $F_\parallel^{\text{BC}}$ (b)

Bootstrap Current in Absence of ECWs

The BC is generated by the temperature and density gradients in the plasma, in the presence of magnetic trapping. In a kinetic description, it results from the antisymmetric DFs f^{BC} and $F_{\parallel}^{\mathrm{BC}}$, shown in Figs. 2 (a),(b) at the radial location $\rho = 0.8$. It is interesting to note that both trapped and passing electrons contribute to the BC. The local bootstrap current density is found to be $\langle J^{\mathrm{BC}} \rangle = 162$ kA/m^2, which is slightly higher than the local OKCD.

Self-Consistent Calculation of OKCD with BC

Taking the same ECW parameters as before, OKCD is calculated self-consistently with the BC, at the radial location $\rho = 0.8$. The interaction of OKCD with the BC is described by the synergistic DFs f^{S} and $F_{\parallel}^{\mathrm{S}}$, which are shown in Figs. 3 (a),(b). The synergism can be interpreted as the effect of the BC on OKCD. Because $f^{\mathrm{BC}} < 0$ in the counter-passing resonant region of momentum space, the ECW induced trapping is reduced, and OKCD as well. However, $f^{\mathrm{BC}} > 0$ on the co-passing side where detrapping occurs, which increases OKCD. In addition, the negative, FBM current is reduced because $f^{\mathrm{BC}} < 0$ in the resonant region of momentum space, which also contributes to increase OKCD. The resulting effect is a BC enhancement of OKCD by $\langle J^{\mathrm{S}} \rangle = 8$ kA/m^2. This synergistic current represents about 7% of OKCD if calculated ignoring BC. p_d^{TOT} is found to be 258 kW/m^3, so the density of power absorbed is almost unaffected by the BC, and the figure of merit is therefore also slightly enhanced: $\eta = 0.45$ A$\cdot$m/W, a 7% synergism. The DKE code with ray tracing gives $I^{OK} \simeq 8$ kA with $I^S \simeq 1$ kA. As shown on Fig. 4, it is deposited at $\rho = 0.8$ in $\Delta\rho \leq 0.05$.

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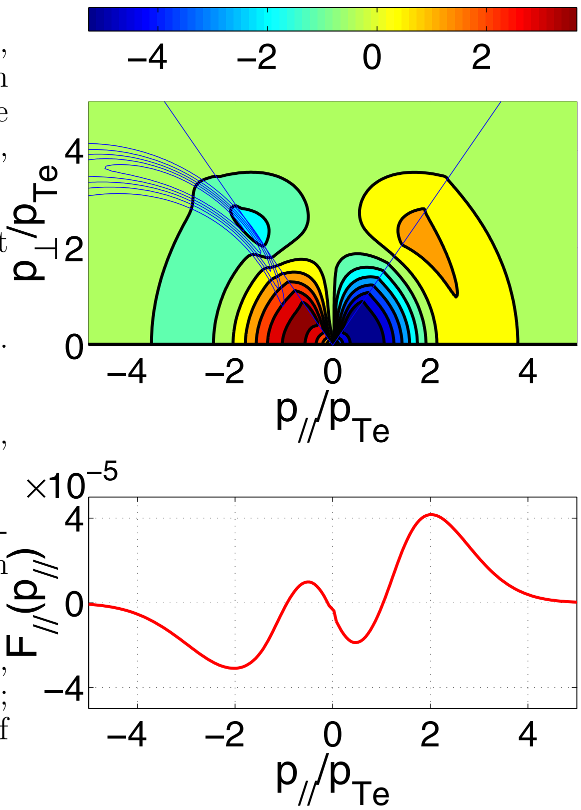

Figure 3: $f^{\mathrm{S}}(a)$ and $F_{\|}^{\mathrm{S}}$ (b)

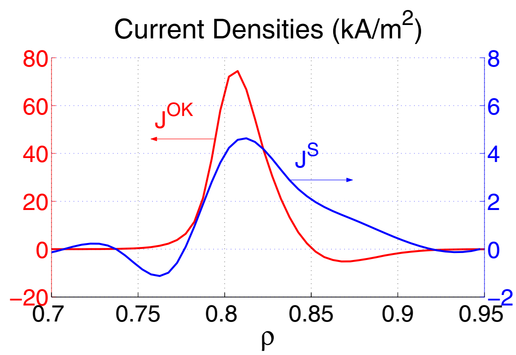

Figure 4: OKCD + Syn. current densities