Current Drive Due to Localized Electron Cyclotron Power Deposition in DIII-D

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Abstract

Due to spatial localization of EC wave injection in DIII-D, electrons heated in an off-axis region must toroidally transit the tokamak 25-50 times before re-entering the heating region. This distance is of the order of the mean free path. The effect of such RF localization is simulated with a time-dependent Fokker-Planck code which is 2D-in-velocity, 1D-in-space-along-B, and periodic in space. An effective parallel electric field arises to maintain continuity of the driven current. Somewhat suprisingly, the localized CD efficiency remains equal to the uniform medium result.

Electron cylotron ray paths from the launcher in DIII-D typically intercept about two percent of the poloidal circumference of a flux surface at half the minor radius. Thus, for a typical non-rational value for the safety factor q, it is expected that after an electron is accelerated by the EC in the “heating spot”, it will make an average of 50 turns around the torus before re-entering the heating spot. This connection distance is approximately equal to the mean free path for thermal electrons, equal to 30 toroidal turns for $T_e = 1.2\,keV$, $n_e = 1.7\,10^{13} cm^{-3}$. Electron cyclotron current driven in the EC spot in an off-axis flux surfaces will collisionally slow down in the resulting current channel; an effective electric field arises maintaining current continuity in the channel. This picture is quite different from the usual toroidally symmetric, bounce-averaged calculation of ECCD [e.g., by CQL3D, [1]].

The motivation for this study is recent experimental results by Luce et al.[2] which found agreement between the DIII-D experiment and detailed Fokker-Planck calculations of ECCD for on-axis cases, and substantially higher experimental results than theory for off-axis ECCD. The present work examines the effect of the localized EC spot size on the ECCD efficiency, but does not include the effect of variation of the magnetic field strength following the magnetic field line. A related paper by Lin-Liu et al.[3] has examined collisional reduction of the toroidal trapping, and finds that this is a small effect on ECCD efficiency for DIII-D parameters.

The Fokker-Planck equation solved for electrons in this study is

$$\frac{\partial f(v,\theta\, s,t)}{\partial t} + v_{\parallel}\frac{\partial f}{\partial z} - \frac{eE_{\parallel}}{m}\frac{\partial f}{\partial v_{\parallel}} = C(F) + Q(f) \tag{1}$$

C is the full non-linear collision operator[4], except that the P_0 term in the Legendre expansion for the electron field particles is a fixed Maxwellian distribution thus enabling a steady state solution. Q is a RF quasilinear operator: $\partial/\partial v_{\parallel}(D_{\parallel}\partial/\partial v_{\parallel} f)$ or $\partial/\partial v_{\perp}(D_{\perp}\partial/\partial v_{\perp} f)$. This equation is solved by finite-differences using an alternating-direction-implicit algorithm described in Sauter *et al.*[5]. The quasi-neutral electric field $E_{\parallel}$ is calculated using a variant of the constant-particle-flux algorithm first described in Kupfer *et al.*[6], with the added equation that the one-turn loop voltage due to the calculated electrostatic field is zero.

Equation (1) has been solved for a range of cases: $v_{\parallel} \sim 1$, $D_{\perp}/D_{coll} = [0.1, 10]$, $\lambda_{mfp}/L = [0.1, 10]$, and parallel or perpendicular velocity diffusion. D_{coll} is $v_{Te}^2 \nu ee$, where $v_{Te} = \sqrt{T_e/m}$. Figure 1 shows the time evolution of the parallel electric field for one particular case with parameters near those for the half-radius heating in DIII-D: $D_{\perp}/D_{coll} = 1.0$ inside the RF region, for velocity $v_{\parallel}$ in $[1, 1.33]v_{Te}$, and $\lambda_{mfp}/L = 1.0$. Time is normalized to L/v_{max}, v_{max} being the maximum velocity on the velocity grid. The length of the RF region has been taken to be 0.2 in units normalized to L. Figure 2 gives the steady state force due to the electric field, and the pressure variation.

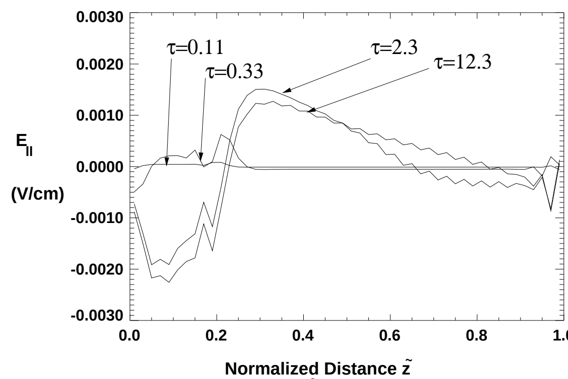

Figure 1: Evolution of the parallel electric field. The normalized perpendicular diffusion coefficient is 1.0 and mean free path is equal to the connection length L.

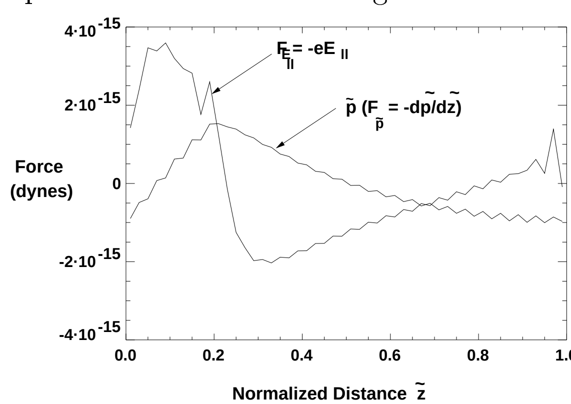

Figure 2: Steady state electric field and normalized pressure variation

In Fig 1, the electric field at first ($\tau = 0.11$ and 0.33) evolves as one might expect: it becomes slightly positive in the RF region from $\tilde{z} = 0$ to 0.2, giving a negative force resisting the positive flow of electrons in the RF region. In the region outside the RF, a negative electric field develops, maintaining the positive motion of the electrons. But as the electron distribution evolves towards a steady state, the electric field changes sign. Figure 2 shows the steady force $F_{E_{\parallel}}$ due to the electric field, which further accelerates the electrons in the RF region. This force is comparable to the Ohmic force, for the case that the RF driven current density is of order the Ohmic current density. From Fig. 2, the pressure $\tilde{p}$, normalized so that the force $F_{\tilde{p}} = \partial \tilde{p}/\partial \tilde{p}$ is in dynes, is larger than the electric field force. It is the effective electric field $E_{\|}'$ which accelerates electrons after they leave the RF region, thereby maintaining current continuity. In simple, near-Maxwellian cases, this will be $E_{\|}' = E_{\|} + (1/n_e e)(\partial p/\partial z)$. For low collisionality, non-Maxwellian cases the effective electric field will involve an integral over velocity space giving the non-local frictional force on the electrons. The extent to which the electric force or the "pressure" force dominates has a rich dependence on the major parameters of the problem.

Plots of the distribution functions versus $\tilde{z}$ show the buildup of the non-Maxwellian distribution within the RF region, and its dissipation as a function of $\tilde{z}$ outside of the RF region.

A range of simulations has been carried out and the results are shown in the following tables for parallel (lower hybrid-like) and perpendicular (EC-like) diffusion. Table 1 shows results for parallel quasilinear diffusion, for two different velocity ranges: $v_{\|} = 3 - 4$, and $v_{\|} = 1 - 1.33$. Several values of $D_{\|}/D_{coll}$ have been explored, and λ_{mfp}/L takes on values from 0.1 to 10.0. Current drive efficiency has been calculated for each of these cases and also for a comparable spatially uniform application of the QL diffusion with the same space-averaged diffusion coefficient. The calculated efficiencies are in good agreement with previous Fokker-Planck results, including low phase velocities. The general result from the present study is that the current drive efficiency varies very little from the uniform to the non-spatially-uniform quasilinear model, regardless of the collisionality. The largest variation between the uniform and non-uniform values is for case "rf_10" giving an 8 percent difference. There is negligible variation in CD efficiency when collisionality λ_{mfp}/L is varied by two orders of magnitude from 0.1 to 10.

Table 1. CD Efficiency forVariations on Parallel Diffusion

Designator	Velocities	$D_{\|}/D_{coll}$ (avg)	λ_{mfp}/L	Loc/Uniform	δ_{CD}
rf_8	3-4	0.002	1.0	L	0.0459
				U	0.0458
rf_10		0.2		L	0.0479
				U	0.0515
rf_14	1-1.33	0.002		L	0.0321
				U	0.0322
rf_12		0.2		L	0.0331
				U	0.0324
rf_16		2.0		L	0.0379
				U	0.0338
rf_14_long		0.002	0.1	L	0.0323
rf_14_short			10.0	L	0.0320

The same range of calculations, shown in Table 2, has been carried out for the case of perpendicular QL diffusion, applicable in the ECCD case. The same broad result is evident from the Table: the CD efficiency is approximately independent of whether the QL diffusion is applied locally or globally.

Table 2. CD Efficiency for Variations on Perpendicular Diffusion

Designator	Velocities	$D_{\|}/D_{coll}$ (avg)	λ_{mfp}/L	Loc/Uniform	δ_{CD}
rf_9	3-4	0.002	1.0	L	0.0259
				U	0.0259
rf_11		0.2		L	0.0264
				U	0.0261
rf_15	1-1.33	0.002		L	0.0101
				U	0.0101
rf_13		0.2		L	0.0099
				U	0.0100
rf_17		2.0		L	0.0088
				U	0.0096
rf_15_long		0.002	0.1	L	0.0101
rf_15_short			10.0	L	0.00998

The reason for the independence of efficiency from collisionality is that the work done on the plasma by the effective electric field over one period of the loop is zero: $\oint E_{\|}^{'}.dz = 0$. The effective electric field is a combination of electrostatic and pressure forces with zero loop integral. Evidently, for the experimentally relevant parameters studied, there is small synergy between these forces and the applied RF. It is conceivable that some effects will appear at higher powers.

In conlusion, we have used a 2-velocity-1-space-D Fokker-Planck code to calculated RF current drive efficiency for both spatially localized and uniformly applied RF power. An effective electric field was found to be the key new effect maintaining continuity of the RF induced current in current channels with $\lambda_{mfp} \leq L$. No substantial change in the CD efficiency from uniform RF calculations was obtained, at experimentally relevant RF power densities. This reinforces the use of a toroidally symmetric approximation in CQL3D.

Acknowledgement: This research was supported by the U.S. DOE under Contract DE-AC03-99ER54463 and in part by the Swiss National Science Foundation.

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