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Decrease in Trapping Effects for Off-Axis Electron Cyclotron Current Drive in High Performance Plasmas

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Abstract: Increased efficiency of off-axis electron cyclotron current drive (ECCD) has been obtained in discharges in DIII–D with higher electron beta, and these results have been understood by studying computationally the particle fluxes in velocity space driven by the EC waves. The relativistic cyclotron resonance tends to shift away in velocity space from the trapped-passing boundary for low-field-side launch as the electron temperature and/or density rise, increasing the net efficiency toward that of the trapping-free Fisch-Boozer level. Calculations with the CQL3D Fokker-Planck code illustrate clearly that the flux in velocity space due to rf-induced diffusion moves away from the trapping boundary for values of β_e which have been realized in the experiments.

Electron cyclotron current drive (ECCD) is a key element of the program on DIII–D to develop high performance discharges which have potential for economical steady-state operation. The ECCD is needed to sustain the current profile which supports improved confinement and stability and to stabilize MHD activity like neoclassical tearing modes. These applications require that the current be driven at a normalized minor radius of 0.5 to 0.8 where the magnetic well depth is large, so that the trapping of electrons in the well may cause a decrease in the efficiency of current drive. Substantial progress on off-axis ECCD has been made in experiments on low performance L–mode plasmas which make a good test-bed for studying the physics of ECCD [1,2]. These experiments showed a strong decrease in CD efficiency for large minor radius. More recent experiments [3] show that this decrease in normalized efficiency at large minor radius becomes smaller for plasmas with higher β_e. This paper focuses on the reduction of the deleterious effects of trapping at higher electron temperature and density which is exhibited in these experiments.

The electron cyclotron resonance for low-field-side launch of waves near the second harmonic is

$$\omega = 2\Omega_0/\gamma + k_{||}\, v_{||} \tag{1}$$

where ω is the applied frequency, Ω_0=eB/m is the nonrelativistic cyclotron frequency, γ is the relativistic factor, $k_{||}$ is the applied wavenumber, and $v_{||}$ is the parallel velocity of a resonant electron. Defining $y=(\omega/2\Omega_0)^2$ and $n_{||}=ck_{||}/\omega$, this becomes

$$\frac{v_\perp^2}{v_t^2} = \frac{1-y}{v_t^2}c^2 + \left[\frac{2n_{||}yc}{v_t}\right]\frac{v_{||}}{v_t} - \left(1+n_{||}^2 y\right)\frac{v_{||}^2}{v_t^2} \tag{2}$$

where $v_t = c[(T_* + T_*^2/4)/(1+T_* + T_*^2/4)]^{1/2}$ is the thermal velocity and $T_*=kT_e/mc^2$ is the electron temperature normalized to the rest mass energy. In this equation the velocities are normalized by v_t in order to connect most simply to plasma physics in which the distribution function is proportional to $\exp[-(v/v_t)^2]$.

For the purposes of this study the key is to evaluate Eq. (2) at the physical location where wave power is absorbed at the maximum rate per unit ray length. This is done for some particular set of conditions, namely the equilibrium, the kinetic profiles ($T_e(\rho)$, $n_e(\rho)$, $Z_{eff}(\rho)$), and the EC ray launching angles. Note that this location is not the maximum of the absorption coefficient along the ray path, since the ray may be well attenuated before reaching that location. The ray tracing code TORAY-GA is used to determine the coordinates (R,z) of the maximum attenuation rate, and the local T_e, $n_{||}$, and B then fully determine the resonance curve for that location.

This computational process has been applied to the conditions of an earlier experiment [1,2], a discharge with the EC wave launched so as to intersect the resonance directly above the magnetic axis at a normalized minor radius of 0.4. The resonance curve is shown in Fig. 1. Also drawn is the trapped-passing boundary, which is simply a straight line drawn through the origin at an angle $\mathrm{asin}[(B_{local}/B_{max})^{1/2}]$ from the vertical axis, with electrons above the boundary trapped. The resonance clearly lies in the vicinity of the trapped region and an interaction with the boundary may be expected.

The temperature and density in the calculation may be artificially changed to illustrate their effects on the resonance. For example, Fig. 1 shows three other cases. In these other cases, the ray launching angles in the calculation were changed slightly or the toroidal magnetic field was adjusted by up to 5% to keep the location of the maximum absorption rate and the $n_{||}$ there constant for all cases. First, n_e was increased by a factor 3. Because there are more electrons the wave absorption coefficient is larger, so the location of maximum attenuation moves further from the cold resonance, requiring a larger Doppler shift in Eq. (1). This shows up as a shift in the resonance curve in Fig. 1 to the right, away from the trapping boundary even though Eq. (2) has no explicit dependence on density. Alternatively, T_e was increased by a factor 3. Since higher T_e also increases absorption this also shifts the resonance curve to the right. Raising T_e has the additional effect of curving the resonance away from the trapping boundary due to

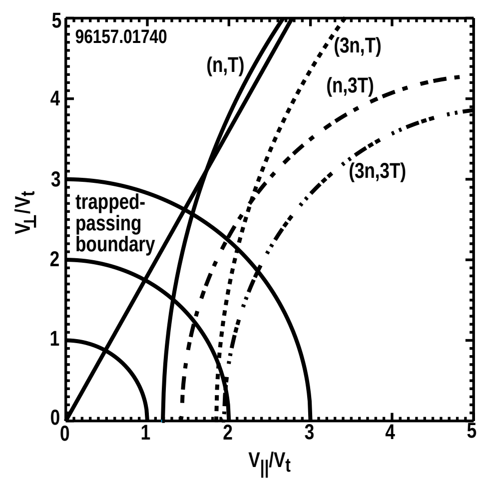

Figure 1. The electron cyclotron resonance curve plotted as a function of $v_\perp/v_t$ and $v_{||}/v_t$ for the experimental conditions (solid curve, n_e=1.57x10^{19} m^{-3}, T_e=1.29 keV, $n_{||}$=0.518) and for other conditions (dashed curve: 3 times higher n_e; dotted curve, 3 times higher T_e; and chain dash, both n_e and T_e 3 times higher). Also shown is the trapped-passing boundary for the mirror ratio 1.23. The plasma is an L–mode discharge in DIII–D with low electron beta of 0.2%.

the explicit T_* dependence in Eq. (2). Finally, increasing both n_e and T_e by a factor 3 both shifts the curve and bends it more strongly away from the trapping boundary.

It is this effect of increased density and/or temperature on the location of the resonance relative to the trapping boundary which accounts for the improvement in the efficiency of off-axis ECCD in plasmas with higher β_e. In describing the physics of this effect, the proper dimensionless physical quantities are T_* from Eq. (2) and ω_p^2/Ω_0^2 from the absorption coefficient [4], where ω_p is the plasma frequency. Since both dimensionless variables tend to reduce the effect of trapping, their product β_e may be a suitable shorthand roughly describing their combined effect. As pointed out by Luce [1], the ratio of the driven current to the EC power can be written so as to remove the expected linear density and temperature dependences which can be expected of all current drive approaches which interact with electrons near their thermal velocity:

$$I_{EC}/P_{EC} = \left(\varepsilon_0^2 T_e \big/ e^3\, n_e R\right)\zeta \quad , \tag{3}$$

where ζ is the dimensionless efficiency which can be written as a function of the physically relevant dimensionless parameters as $\zeta=\zeta(n_{||}, M_B, T_*, \omega_p^2/\Omega_e^2)$. The effects and dependences of electron trapping are then isolated in the dimensionless efficiency.

Any electron satisfying Eq. (2) is resonant with the wave. However, not all resonant electrons interact strongly with the wave. For example, absorption of the X2 mode is a finite Larmor radius effect, so electrons with small $v_\perp$ interact only weakly with the wave. In order to see more clearly the electrons which are affected by the wave, the CQL3D Fokker-Planck code [5] was applied to these model cases. CQL3D obtains a solution to the relativistic bounce-averaged Fokker-Planck code including a source term representing the diffusion induced by the rf waves.

The CQL3D calculations for experimental cases clearly show the effect on the normalized efficiency of increasing n_e and T_e. Three discharges at different β_e but approximately the same minor radius ρ=0.4 and poloidal angle 90° (directly above the magnetic axis) were selected from the data set illustrated in Fig. 4 of Ref. [3], and summarized in Table 1. The TORAY-GA code was run for these experimental cases using 30 rays to represent the Gaussian beam, which gives a broadening of the $n_{||}$ spectrum due to the wave divergence. For the highest density case with the largest refraction spreading of the beam, shot 106275, the rms spread in $n_{||}$ is 0.027 while the mean $n_{||}$ is 0.309. Then CQL3D is used to calculate the particle flux in velocity space due to the rf diffusion, $\bar{\bar{D}}_{RF} \cdot \bar{\nabla} f_e$, from the ray paths calculated by TORAY-GA. The magnitude and direction of the fluxes are shown for the three cases in Fig. 2. In the lowest β_e case a significant part of the wave-particle interaction takes place in the close vicinity of the trapping boundary, while in the other two cases the interaction moves further from the boundary and the reduction in current drive efficiency due to trapping is expected to be reduced.

Table 1. Conditions for discharges used in Fig. 2. n_e is local density in 10^{19} m^{-3}, Te in keV

Shot	ρ	β_e(%)	n_e	T_e	$n_{\|\|}$
103969	0.365	0.18	1.25	1.58	0.393
106120	0.379	0.98	4.22	2.23	0.294
106275	0.421	1.79	5.99	2.82	0.309

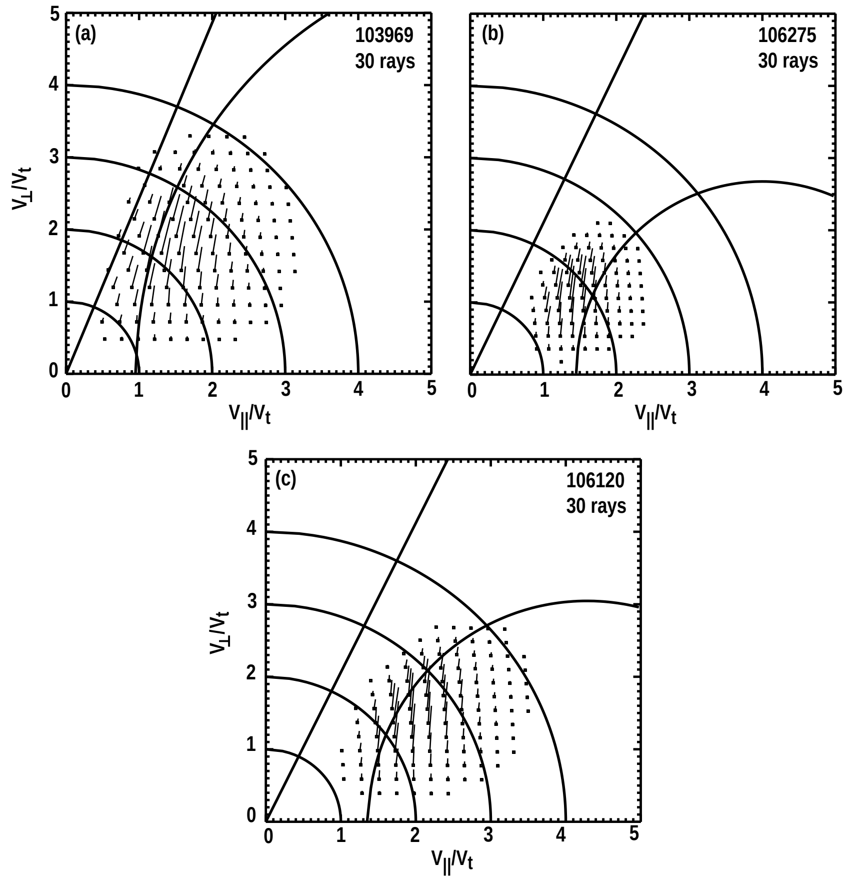

Figure 2. Particle flux in velocity space calculated by CQL3D for the three cases described in Table 1: (a) 103969, (b) 106120, (c) 106275.

In summary, the effects of increasing electron temperature and electron density on the relativistic resonance tend to move the interaction of the wave and the particles away from the trapped-passing boundary in velocity space.

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