Physics of Electron Cyclotron Current Drive on DIII–D*

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Recent experiments on the DIII–D tokamak have focused on determining the effect of trapped particles on the electron cyclotron current drive (ECCD) efficiency. Using internal measurements from the motional Stark effect (MSE) diagnostic, driven currents as small as 1% of the total plasma current can be accurately measured. As a result, the physics of ECCD can be explored in unprecedented detail since the ECCD efficiency can be determined over a wide range of deposition locations, toroidal injection angles and electron betas. The electron beta turns out to be a critical parameter, and the measured efficiency for off-axis ECCD in high beta H–mode plasmas is found to equal the value required for advanced tokamak scenarios on DIII–D. For all of these cases, the measured ECCD has been compared to both the linear theory (*i.e.*, TORAY-GA) as well as a Fokker-Planck calculation including the effect of the parallel electric field (*i.e.*, CQL3D). The experimental ECCD is found to be in better agreement with the more complete Fokker-Planck calculation.

The measured (normalized) efficiency of off-axis ECCD is found to increase with increasing electron beta, which can be explained by reduced electron trapping effects. Tests of electron trapping, shown in Fig. 1, show that the measured ECCD efficiency decreases rapidly with normalized radius (ρ) in low beta plasmas but much less so in high beta plasmas. In this figure, a dimensionless form of the current drive efficiency is used, $\zeta=(e^3/\varepsilon_o^2)\, I_{ec}\, n_e\, R/P_{ec}\, T_e$, which normalizes out the leading theoretical dependencies. For low beta plasmas, the rapid decrease in ζ with ρ is theoretically expected (as shown by the dashed line) since the trapped particle fraction increases with radius, leading to larger electron trapping that reduces the ECCD. However, Fig. 1 shows that the detrimental effects of electron trapping are greatly

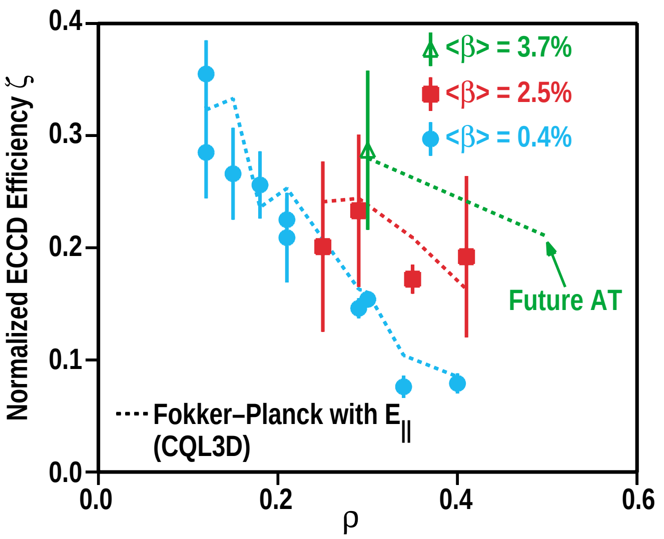

Fig. 1. Experimental ECCD efficiency as a function of the normalized radius of deposition for an L–mode plasma with <β> = 0.4% (circles), an H–mode plasma with <β> = 2.5% (squares), and an advanced tokamak plasma with <β> = 3.7% (triangle) The theoretical ECCD efficiency is also shown (dashed lines).

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diminished at high beta since ζ does not decrease much with increasing ρ for that case. This is explained theoretically by the shift in the electron cyclotron resonance to higher parallel electron velocities due to the stronger damping and relativistic effects in high electron beta plasmas. Thus, the resonant region of velocity space moves further away from the trapped/passing boundary and the current carrying electrons are less likely to pitch angle scatter into the trapped region. Figure 2 shows that the measured ECCD efficiency at fixed radius increases steadily with larger electron beta, with some signs of saturation at the highest beta value. The beta dependence is stronger for more off-axis ECCD since the trapped particle fraction increases with radius. The experimental increase in ζ with electron beta is in reasonable agreement with the theoretical ECCD efficiency (dashed lines). Owing to this favorable beta dependence, high ECCD efficiencies are expected in advanced tokamak plasmas on DIII–D where off-axis ECCD will be used to sustain the hollow current profile. In fact, the measured ECCD efficiency for off-axis deposition in high beta H–mode plasmas is already equal to the value needed for future advanced tokamak scenarios that will use ECCD for current profile control.

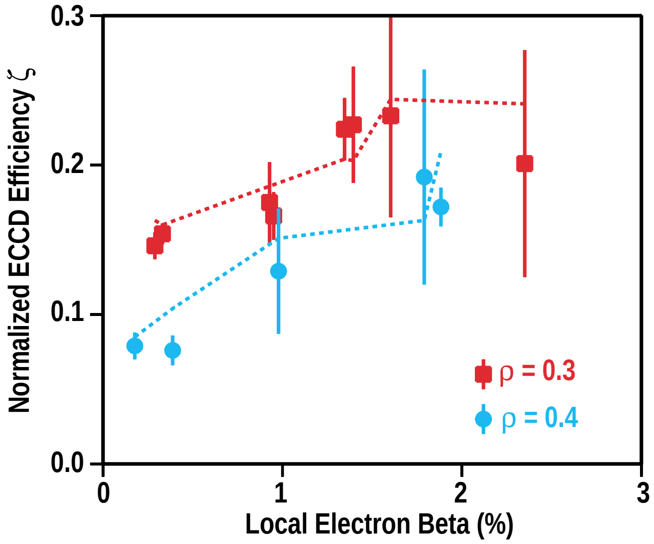

Fig. 2. Measured dependence of the ECCD efficiency on the local electron beta for deposition locations of ρ=0.3 (squares) and ρ=0.4 (circles). The theoretical dependence is also shown (dashed lines).

The ECCD efficiency also has been measured for co, counter, and radial injection. A scan of the toroidal injection angle shows that the ECCD switches from the co to the counter direction, with radial injection driving little current as expected. In low beta plasmas, the experimental counter ECCD efficiency decreases with increasing radius, similar to the co ECCD results in Fig. 1. Furthermore, the current drive efficiency for both co and counter ECCD is measured to decrease as the poloidal location (at fixed ρ) is scanned from the high-field-side to the low-field-side of the machine, which is expected since the local trapped particle fraction is maximum at the outboard midplane. Therefore, the effects of electron trapping are similar for the co and counter ECCD directions. For all of these cases, the measured ECCD magnitude and location are in agreement with quasi-linear Fokker-Planck calculations including the effect of the parallel electric field. In addition, the width of the ECCD profile appears to be no wider than the ray tracing predictions, indicating that current profile broadening by the transport of energetic electrons is minimal, although more study is required in this area.