GA–A23713

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DISCLAIMER

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This is a preprint of a paper to be presented at the 28th European Physical Society Conference on Plasma Physics in Controlled Fusion, Madeira, Portugal, June 18–22, 2001 and to be published in the *Proceedings.*

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Work supported by
the U.S. Department of Energy under
Contracts DE-AC03-99ER54463, W-7405-ENG-48,
and Grant DE-FG03-99ER54541

GENERAL ATOMICS PROJECT 30033
AUGUST 2001

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ABSTRACT

The DIII-D program is making excellent progress towards experimentally validating a predictive model of electron cyclotron current drive (ECCD). Tests of electron trapping show that the measured ECCD efficiency decreases rapidly with radius for both co and counter injection in low beta plasmas, but the ECCD efficiency does not decrease much with radius in high beta plasmas. This shows that the detrimental effects of electron trapping on the ECCD efficiency are greatly reduced at high beta. The measured ECCD efficiency for off-axis deposition in high beta H-mode plasmas is equal to the value needed for future advanced tokamak scenarios that will use ECCD for current profile control.

INTRODUCTION

Localized current drive from electron cyclotron wave absorption near the half radius of the plasma is required to achieve and sustain fully non-inductive current profiles in advanced operating modes on the DIII-D tokamak [1]. Ongoing electron cyclotron current drive (ECCD) experiments on DIII-D are solidifying the physics basis for localized, off-axis current drive in these types of plasmas, the goal being to validate a predictive model of ECCD. In addition to modifying the current profile, the DIII-D program uses electron cyclotron heating (ECH) to probe the plasma transport properties and ECCD to control MHD instabilities [2].

Localized absorption and current drive by electron cyclotron waves have been measured for both L-mode and ELMing H-mode plasmas on DIII-D using second harmonic X-mode launch. The ECCD radial profile can be found from internal magnetic field measurements using motional Stark effect (MSE) spectroscopy, either by comparing the total and ohmic current profiles determined from equilibrium reconstruction [3,4], or by comparing the measured MSE signals to simulations of the expected MSE response to localized current drive [5], as is done in this paper. Recent ECCD experiments discussed here have measured the current drive efficiency as a function of the parallel index of refraction ($N_{||}$) as well as several easily varied parameters that affect the electron trapping, such as the normalized radius of absorption (ρ) and electron beta (β_e). These experiments use up to four gyrotrons with a maximum ECH power of 2.1 MW.

COMPARISON OF CO AND COUNTER ECCD

A scan of $N_{||}$ from positive to negative values shows that the ECCD switches from the co to the counter direction, with radial injection driving little current. This is shown in Fig. 1, where the experimental ECCD is plotted as a function of the toroidal injection angle ($\propto N_{||}$) for a deposition location of r = 0.3 and an ECH power of P_{ec} =1.2 MW. The theoretical ECCD from a quasilinear bounce-averaged Fokker-Planck calculation using the CQL3D code [6], including the effect of the parallel electric field ($E_{||}$), is also given in Fig. 1. The measured ECCD increases from $I_{ec} \approx 0$ for radial launch to $I_{ec} \approx 40$ kA for co current drive launch, in good agreement with the CQL3D code. Theoretically, the ECCD is expected to increase with $N_{||}$ since the electron cyclotron waves interact with higher parallel velocity electrons. For counter injection, Fig. 1 shows that while counter ECCD increases with increasingly more negative $N_{||}$ values, the magnitude is about a factor of two below the prediction. The disagreement between theory and experiment for counter ECCD is not understood presently; among the possible explanations are an incorrect toroidal injection angle, an insensitivity of the MSE signals to current profiles with counter ECCD, and an incorrect bounce average in the calculation of the theoretical efficiency. The parallel electric field has been ruled out as a possible source of the discrepancy.

In low β_e plasmas, electron trapping is found to strongly affect the ECCD since the current drive efficiency decreases with increasing radius of absorption for both the co and counter current directions. This paper uses a dimensionless form of the current drive efficiency [3],

$$\zeta_{ec} = \frac{e^3}{\varepsilon_o^2}\frac{I_{ec} n_e R}{P_{ec} T_e} \qquad (1)$$

$$= 3.27\frac{I_{ec}[\mathrm{MA}]n_e\left[10^{19}\mathrm{m}^{-3}\right]R[\mathrm{m}]}{P_{ec}[\mathrm{MW}]T_e[\mathrm{keV}]} \quad , \qquad (2)$$

where n_e is the electron density, T_e is the electron temperature, and R is the plasma major radius. Figure 2 gives ζ_{ec} for co and counter injection as a function of ρ for a L-mode plasma with <β> = 0.4%. The experimental ECCD efficiency is seen to rapidly decrease with increasing ρ for both co and counter current drive. The theoretical ECCD efficiency calculated by the CQL3D code, including the effect of $E_{||}$, is also seen to strongly decrease with radius for both injection directions in Fig. 2. For co ECCD, theory and experiment are in reasonable agreement, while for counter ECCD, the measured efficiency is about half the theoretical value, similar to the results in Fig. 1. The decrease in ζ_{ec} with ρ is expected since the trapped particle fraction increases with radius, leading to larger electron trapping that reduces the ECCD. This trend would extrapolate to nearly zero current drive efficiency at r ≈ 0.5, the location where ECCD is needed for current profile control in advanced tokamak scenarios on DIII-D [1]. However, the following section will show that off-axis ECCD is more favorable in high β_e plasmas.

ECCD DEPENDENCE ON β_e

Theoretically, the ECCD efficiency is expected to increase with higher electron beta owing to reduced electron trapping effects. This is especially important for off-axis ECCD since the trapped particle fraction increases with minor radius. This effect is illustrated in Fig. 3, where the vectors of the ECH driven flux in velocity space are shown for two L-mode plasmas with β_e = 0.2% and β_e = 1.0%. The ECH driven flux is determined from the CQL3D code at ρ = 0.4. For the low beta case in Fig. 3(a), there is a small angular separation between the location of the ECH driven flux and the trapped/passing

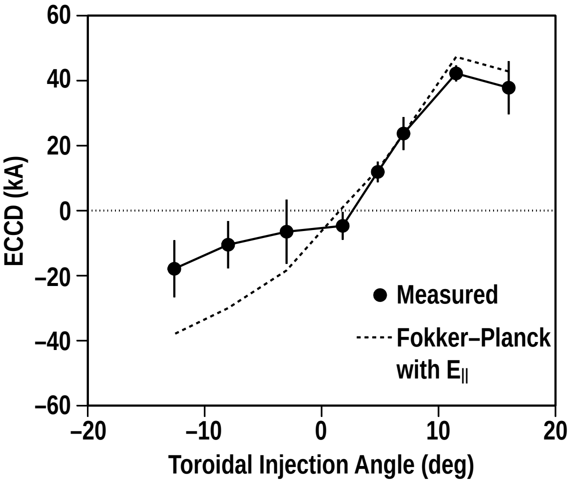

Fig. 1. Dependence of the experimental (filled circles) and theoretical (dashed line) ECCD on the toroidal injection angle of the electron cyclotron waves.

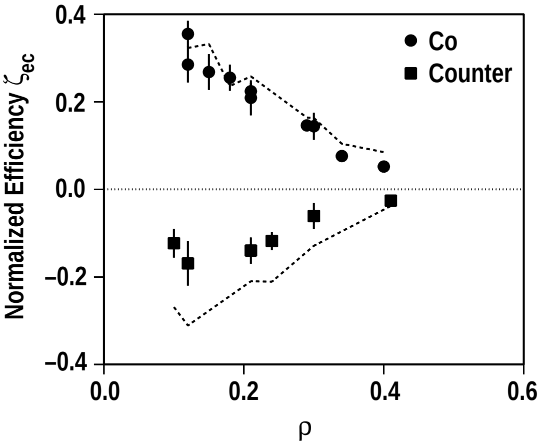

Fig. 2. Experimental ECCD efficiency as a function of the normalized radius of deposition for co (circles) and counter (squares) injection for a L-mode plasma with <β> = 0.4%. The theoretical ECCD efficiency is also shown (dashed lines).

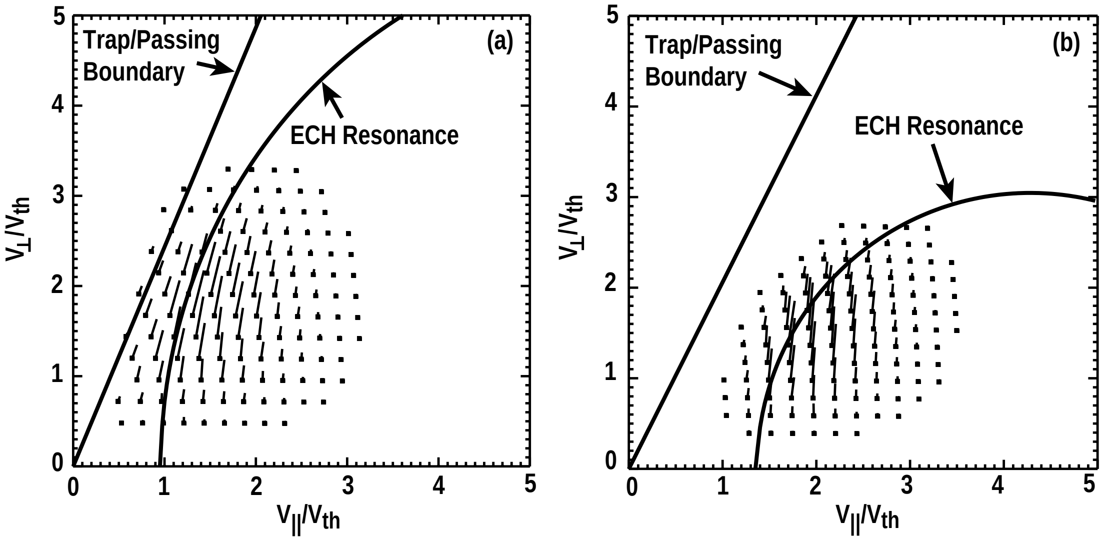

Fig. 3. Vectors of ECH driven flux in velocity space at the resonance location for (a) β_e = 0.2%, and (b) β_e = 1.0%. In this figure, $v_{||}$ is the parallel electron velocity, $v_\perp$ is the perpendicular electron velocity, and v_{th} is the thermal electron velocity.

boundary. Therefore, the current carrying electrons can easily pitch angle scatter into the trapped region of velocity space, reducing the current drive efficiency. On the other hand, for the high beta case in Fig. 3(b), the ECH resonance has been shifted to higher parallel velocities due to the stronger damping and relativistic effects; thus, the ECH resonance is further from the trapped/passing boundary. Since the angular separation between the ECH driven flux and the trapped/passing boundary is greater in this case, the current carrying electrons are less likely to pitch angle scatter into the trapped region of velocity space. The result is that electron trapping effects are reduced in high-β_e plasmas, and the ECCD efficiency is correspondently greater [7].

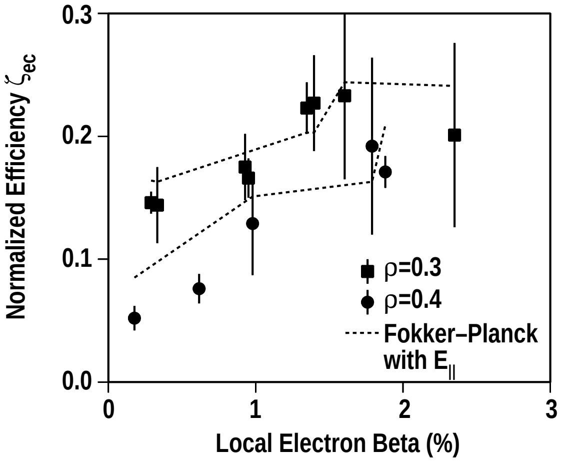

Fig. 4. Measured dependence of the ECCD efficiency on the local electron beta for deposition locations of ρ = 0.3 (squares) and ρ = 0.4 (circles). The theoretical dependence is also shown (dashed lines).

Experimentally, the measured ECCD efficiency for off-axis absorption increases with higher local electron beta, as shown in Fig. 4. For these experiments, β_e is changed by varying the neutral beam heating power and by utilizing both L-mode and H-mode plasmas. At ρ = 0.3, ζ_{ec} is measured to increase by ≈ 50% from low-β_e L-mode plasmas to high-β_e H-mode plasmas, the latter approaching the conditions needed for advanced tokamak scenarios. However, in these same plasmas, a much larger factor-of-four increase in ζ_{ec} is measured at ρ = 0.4 since the electron trapping effects are more important at larger absorption radii. The experimental increase in ζ_{ec} with β_e is in reasonable agreement with the theoretical ECCD efficiency calculated by the CQL3D code, including the effect of $E_{||}$, as shown in Fig. 4. The result is that off-axis ECCD is more favorable in high-β_e plasmas since the ECCD efficiency does not decrease much with radius owing to reduced trapping effects.

CONCLUSIONS

Recent ECCD experiments on the DIII-D tokamak have solidified the physics basis for localized, off-axis current drive. The measured co ECCD is in good agreement with quasilinear Fokker-Planck calculations, including the effect of $E_{||}$, over a wide range of parameters. A scan of the toroidal injection angle shows clearly that the ECCD switches from the co to the counter direction, with radial injection driving little current, although the measured counter ECCD is less than theoretically predicted. Electron trapping is found to strongly affect the ECCD since the normalized current drive efficiency decreases with increasing radius for both the co and counter current drive directions in low-β_e plasmas. However, the ECCD efficiency at $\rho = 0.4$ is measured to increase by nearly a factor-of-four as β_e increases locally by an order of magnitude. This can be explained theoretically by the stronger damping of the electron cyclotron waves with higher density and temperature as well as relativistic effects, causing the ECH resonance to move away from the trapped/passing boundary in velocity space which reduces the deleterious effects of electron trapping. These experiments indicate that an ECCD efficiency of $\zeta_{ec} \approx 0.2$ can be achieved at $\rho = 0.5$ in high beta plasmas, which is what is required for the future advanced tokamak scenarios being developed for DIII-D.

ACKNOWLEDGMENT

Work supported in part by the U.S. Department of Energy under Contracts DE-AC03-99ER54463, W-7405-ENG-48, and Grant DE-FG03-99ER54541.

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