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USING ECCD ON DIII-D**

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Complete Suppression of the $m=2/n=1$ NTM Using ECCD on DIII-D

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Abstract. Complete suppression of the $m=2/n=1$ neoclassical tearing mode (NTM) is reported for the first time using electron cyclotron current drive (ECCD) to noninductively generate current at the radius of the island O-point. Experiments on the DIII-D tokamak show that the maximum shrinkage of the $m=2/n=1$ island amplitude occurs when the ECCD location coincides with the $q=2$ surface. Estimates of the ECCD radial profile width from the island shrinkage are consistent with ray tracing calculations but may allow for a factor-of-1.5 broadening from electron radial transport.

INTRODUCTION

Neoclassical tearing modes (NTMs) are magnetic islands that grow from a finite amplitude initial condition owing to a helical deficit in the bootstrap current that is resonant with the spatial structure of the local magnetic field [1]. The onset of NTMs represent a significant limit to the plasma performance at higher poloidal beta. For example, high beta values often destabilize the $m=2/n=1$ mode that can lock to the wall, grow rapidly and disrupt the plasma [2]. Here m is the poloidal mode number and n is the toroidal mode number for tearing modes resonant at safety factor $q=m/n$. Several tokamaks have demonstrated the suppression of the $m=3/n=2$ NTM using ECCD positioned at the $q = 1.5$ location [3–5].

This paper reports the first use of ECCD to suppress the important $m=2/n=1$ neoclassical tearing mode on DIII-D. Up to five gyrotrons operating at 110 GHz are used in these experiments, with a maximum combined power of 2.7 MW absorbed in the plasma. The poloidal cross-section of the DIII-D plasma, the electron cyclotron wave trajectories and the electron cyclotron resonances are shown in Fig. 1. The electron cyclotron waves first pass through the third harmonic of the electron cyclotron frequency ($3 f_{ce}$) where less than 5% of the power is calculated to be damped before propagating on to the second harmonic resonance ($2 f_{ce}$) where the remaining power is absorbed. To drive current at the same location as the $m=2/n=1$ NTM, the launching antennas are steered so that the electron cyclotron waves are absorbed near the $q=2$ surface, as indicated in Fig. 1.

COMPLETE SUPPRESSION OF THE $m=2/n=1$ NTM BY ECCD

Complete suppression of the $m=2/n=1$ NTM has been achieved for the first time using ECCD to replace the “missing” bootstrap current at the $q=2$ surface. A comparison of two discharges, one with complete suppression of the $m=2/n=1$ NTM and one with only partial suppression, is given in Fig. 2. The energy content is regulated using closed loop feedback of the neutral beam injection (NBI) power in these discharges. The $m=2/n=1$ NTM is triggered by temporarily raising the feedback value of normalized beta (β_N) until it reaches the ideal limit for a plasma without a conducting wall ($\approx 4 \ell_i$, where ℓ_i is the internal inductance); the feedback value of β_N is then reduced to avoid driving the tearing mode to a large amplitude. Soon after the tearing mode starts to grow, 2.7 MW of ECCD is injected into the plasma near the island location, driving 40 kA of current according to the CQL3D quasilinear Fokker-Planck code [6]. For the complete suppression case in Fig. 2 (solid lines), the plasma control system (PCS) is put into a “search and suppress” mode to make small changes in B_T to find and hold the optimum ECCD position for island stabilization. Figure 2 shows that the PCS makes one adjustment to B_T of ≈ 0.01 T (equi-valent to moving the ECCD location by 0.9 cm along the midplane), after which the $m=2/n=1$ NTM is completely suppressed.

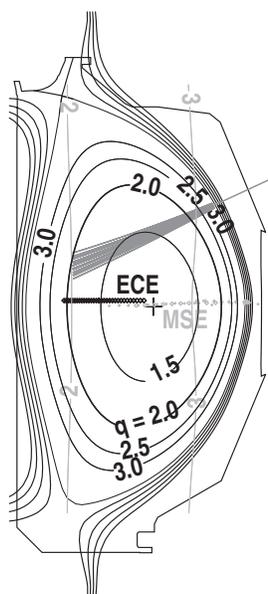


Figure 1. Configuration for NTM suppression using ECCD showing the q surfaces, 2nd and 3rd harmonic resonance locations, and projection of the electron cyclotron wave trajectories. The locations of the ECE and MSE measurements are also indicated.

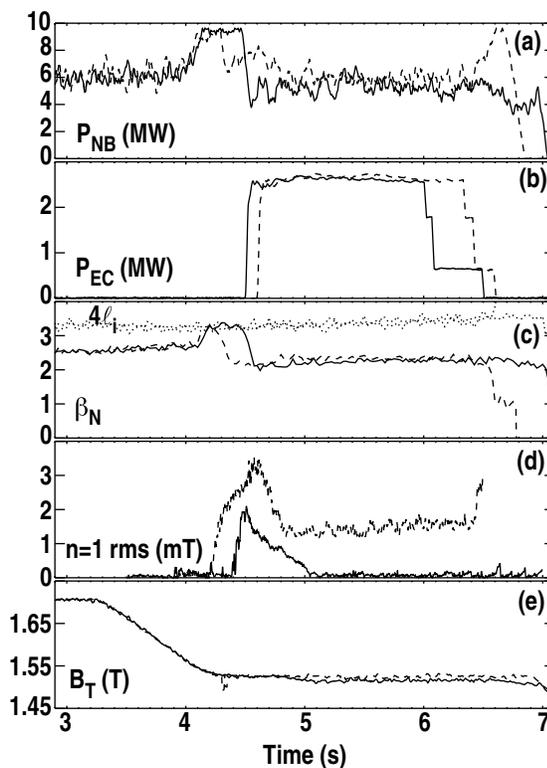


Figure 2. Time history of complete suppression (solid lines) and partial suppression (dashed lines) discharges showing (a) NBI power, (b) ECCD power, (c) normalized beta and ideal no-wall stability limit (dotted lines), (d) rms amplitude of $n=1$ tearing mode measured at the wall, and (e) toroidal magnetic field strength.

For the partial suppression case (dashed lines), the B_T value and thus the ECCD location is not optimized.

SENSITIVITY TO ECCD LOCATION AND WIDTH

Experiments on DIII-D show that the suppression of the $m=2/n=1$ NTM is sensitive to the location of the ECCD with regard to the $q=2$ surface. This is shown in Fig. 3, where the normalized radius of the $q=2$ surface ($\rho_{q=2}$) determined from equilibrium reconstruction and the normalized radius of the ECCD location (ρ_{EC}) determined from ray tracing codes [7,8] are plotted during the course of a B_T scan. The amplitude of the $m=2/n=1$ NTM measured by Mirnov coils outside the plasma reaches a minimum when the ECCD passes through the $q=2$ surface.

Finally, modeling the island shrinkage due to localized ECCD allows an upper limit to be placed on profile broadening caused by radial transport of the current carrying electrons. The evolution of the radial width (w) of the tearing mode is modeled by the modified Rutherford equation [5],

$$\frac{\tau_R}{r} \frac{dw}{dt} = \Delta' r + \varepsilon^{1/2} \left(\frac{L_q}{L_p} \right) \beta_{pol} \left[\frac{rw}{w^2 + w_d^2} - \frac{rw_{pol}^2}{w^3} - \frac{8qr\delta_{EC}}{\pi^2 w^2} \left(\frac{\eta J_{EC}}{J_{BS}} \right) \right], \quad (1)$$

where J_{EC}/J_{BS} is the peak ECCD current density normalized to the local bootstrap current density, $\eta = 0.4/(1 + 2\delta_{EC}^2/w^2)$ for non-modulated ECCD with perfect alignment between the peak ECCD and the island O-point, δ_{EC} is the FWHM of the ECCD radial profile, and the other terms are defined in Ref. [5]. Radial transport of the current carrying electrons enters into Eq. (1) in two ways: δ_{EC} increases and J_{EC}/J_{BS} decreases. Assuming that the total driven current is independent of δ_{EC} , the net effect of electron radial transport is unfavorable for mode suppression. Figure 4 shows the calculated $m=2/n=1$ island width from Eq. (1) as a function of δ_{EC} for the discharge shown in Fig. 3 at time 5.6 s when the mode has reached its minimum amplitude and $dw/dt = 0$. The TORAY-GA code calculates a peak ECCD current

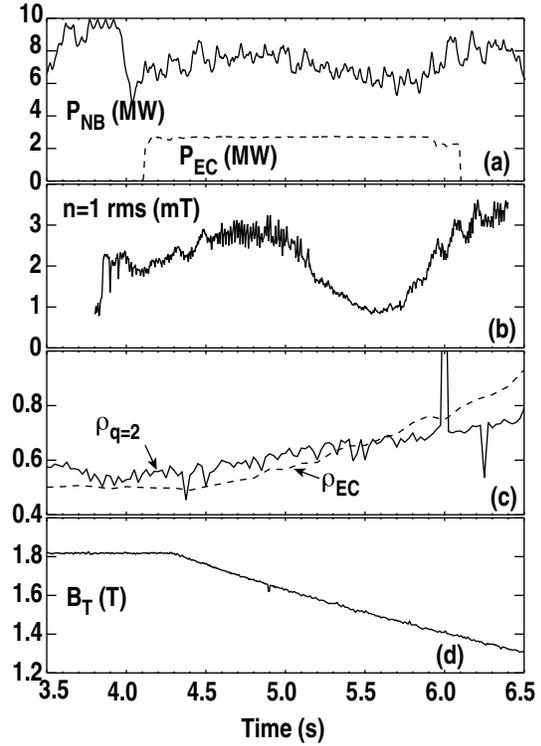


Figure 3. Time history B_T sweep showing (a) NBI (solid) and ECCD (dashed) powers, (b) rms amplitude of the $n=1$ tearing mode measured at the wall, (c) normalized radius of $q=2$ surface (solid) and ECCD location (dashed), and (d) toroidal magnetic field strength.

density that is 2.5 times the local bootstrap current density for $\delta_{EC} = 2.6$ cm in the absence of electron radial transport. For fixed ECCD magnitude, $J_{EC}/J_{BS} \propto \delta_{EC}^{-1}$. Figure 4 shows that the predicted minimum width of the $m=2/n=1$ island during the B_T ramp increases with increasing δ_{EC} , with $\delta_{EC} = 2.6$ cm being very close to achieving complete elimination of the island according to Eq. (1). The measured island width of 8 cm is also indicated in Fig. 4. The theoretical and experimental island widths agree for an ECCD profile width of 3.3 cm with a lower limit of 2.6 cm and an upper limit of 3.9 cm. Modeling this amount of ECCD profile broadening using CQL3D places an upper limit of 0.7 m²/s on the fast electron transport.

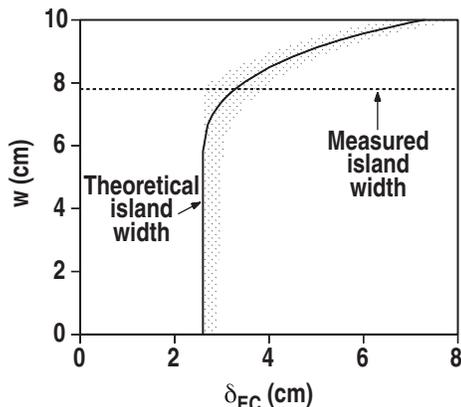


Figure 4. Predicted minimum width from Eq. (1) of $m=2/n=1$ island (solid line) during B_T sweep; the error bars are due to the 10% uncertainty in the gyrotron power. The measured minimum island width is also indicated.

SUMMARY

For the first time, the important $m=2/n=1$ NTM has been completely suppressed using co-ECCD on the DIII-D tokamak. By noninductively driving a small fraction of the total plasma current (typically 3%) within the island located at the $q=2$ surface, the non-modulated ECCD is able to replace the “missing” bootstrap current and the $m=2/n=1$ NTM can be stabilized. Modeling of the island shrinkage using the modified Rutherford equation indicates that the width of the ECCD radial profile is consistent with ray tracing calculations but may also allow for a factor-of-1.5 broadening due to radial transport of the current carrying electrons.

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