Onset and Suppression of 2/1 NTM in DIII-D* EX-S

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Complete suppression of the important m=2/n=1 neoclassical tearing mode (NTM) has been achieved recently in DIII-D using electron cyclotron current drive (ECCD) in the island O-point [1]. High performance, hybrid-regime discharges were used in these experiments with $\beta_N \approx 2.8$ ($\beta \approx 3.5\%$), which equals 90% of the ideal kink no wall stability limit. These NTMs were shown to be classically destabilized by varying $d\beta/dt$ prior to onset and comparing the resulting island growth rate to a comprehensive model. Using five gyrotrons with 2.7 MW of unmodulated power to drive 40 kA of current at ρ=0.66 (the location of the q=2 surface), this NTM was stabilized resulting in a ≈30% improvement (recovery) of the energy confinement time and an increase in the toroidal rotation velocity. This demonstration of the complete suppression of the m=2/n=1 NTM using ECCD improves confidence that a control system to prevent confinement loss and disruptions arising from this mode can be developed in ITER.

Maximum shrinkage of the m=2/n=1 island size occurred when the co-injection ECCD was precisely aligned with the q=2 surface, the latter location determined from equilibrium reconstructions and fluctuations in the electron cyclotron emission at the island rotation frequency. The effects of heating and current drive on the NTM suppression were separated experimentally by comparing resonance location scans for co, radial, and counter injection of the electron cyclotron waves. Co-injection resulted in the maximum shrinkage of the m=2/n=1 island width, while a much smaller island shrinkage was observed for radial injection. The island size increased for counter-injection, leading to a larger loss in confinement. Increasing the co ECCD power to 2.7 MW resulted in the complete suppression of the m=2/n=1 NTM by driving a small fraction of the total plasma current (typically 3%) within the island O-point. The DIII-D plasma control system (PCS) was put into a "search and suppress" mode to make small changes in the toroidal field strength to find and lock onto the optimum ECCD position, based on real time measurements of dB_θ/dt, for complete suppression of the m=2/n=1 NTM. Figure 1 shows a comparison of two discharges, one with the ECCD position optimally tuned by the PCS and complete suppression of the NTM, and one with the ECCD location fixed ≈0.10 m away from the optimal value and no suppression. The former discharge has better confinement as evident from the reduced NBI power. Experiments are planned to raise β_N up to or beyond the ideal kink no wall stability limit after m=2/n=1 NTM suppression by ECCD with active tracking of the position of the resonant

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surface for the mode using the PCS. The conditions for which complete m=2/n=1 NTM suppression was obtained are well modeled by the modified Rutherford equation. In particular, the experiments confirmed the model prediction that for a given rf current density (i.e., for a given ECCD power) there is an upper limit to the value of β_P for which the mode could be stabilized.

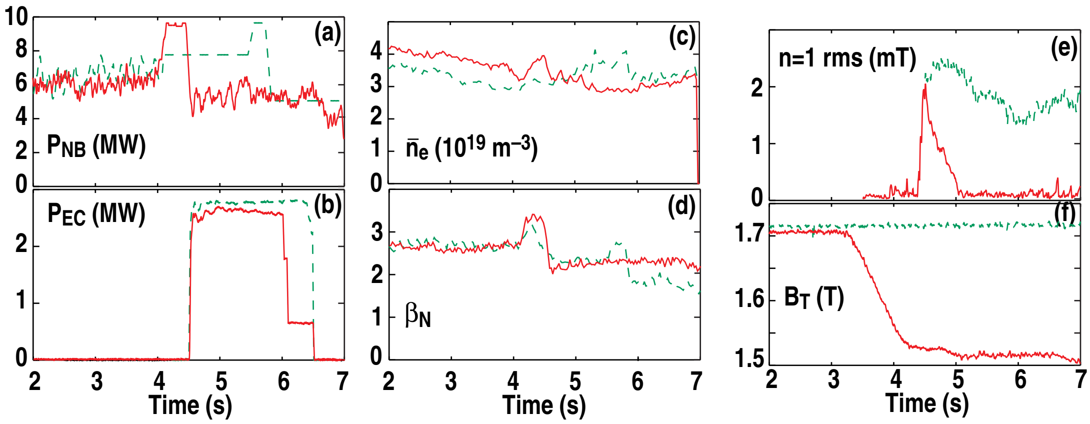

Fig. 1. Time history of discharges with ECCD on the q=2 surface (solid red lines) and ECCD off the q=2 surface (dashed green lines) showing (a) NBI power, (b) ECCD power, (c) line-average density, (d) normalized beta, (e) rms amplitude of n=1 tearing mode measured at the wall, and (f) toroidal magnetic field strength.

In addition to demonstrating the suppression of the m=2/n=1 NTM, the mode onset was also studied using a comprehensive model in which analytic, linear computational and nonlinear simulation results are compared to experimental data to explain the important physics and categorize the onset mechanisms. A framework is presented for understanding the range of tearing phenomena in terms of the interactive dynamics of equilibrium, stability and transport under external driving factors, which yields a range of dynamical solutions in agreement with experiment. The time dependence of the linear stability index Δ' as a function of β [2] is a critical physics element which, when combined with neoclassical [3] and polarization [4] effects, leads to limits in the rate of change in β beyond which fundamentally different behavior of the system is predicted and observed in DIII-D. A series of DIII-D experimental cases that exemplify the onset and evolution physics of classically destabilized NTMs is compared to analytic and numerical limits on the rate of change in β on approach to the onset of NTMs.

Classically destabilized NTMs are analyzed in the fast and slow heating regimes, and the model thus predicts maximum and minimum rates of heating for immediate NTM onset. In the fast heating regime, the change in the linear stability as β approaches the ideal limit dominates the evolution [5], and the tearing mode grows faster than the rate of current relaxation. Above the maximum rate the integrated growth time of the tearing mode is longer than the heating time, and the ideal mode becomes unstable before the NTM can grow. In the slow heating regime, the effect of the enhancement of transport losses dominates the evolution through the modification of the current distribution and concomitant change in the linear stability. In this case the tearing mode grows slowly enough to be affected by the redistribution of current. Below the minimum rate, the seed island does not evolve into a large NTM but remains saturated at a small size. Between the upper and lower rate limits, classically destabilized NTMs are observed, and the β value that is reached as a function of island size is predicted and agrees with experiment. Nonlinear initial value simulations are used to test the predictions from the simple models and give insight into how mode coupling effects the evolution. These results suggest strongly that this onset mechanism operates in DIII-D.

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