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Effects of Electron Cyclotron Current Drive, Counter-NBI, and Rotational Entrainment on Neoclassical Tearing Mode Control in DIII-D

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Abstract. The neoclassical tearing mode (NTM) plays an important role in the performance of tokamak plasmas, and electron cyclotron current drive (ECCD) can stabilize the NTM. The m=2/n=1 NTM has been observed to strongly degrade confinement and frequently lead to a disruption in high beta discharges in DIII-D if allowed to grow to large size. The onset of the 2/1 NTM has been avoided altogether in DIII-D discharges at beta values up to the no-wall beta limit by preemptively applying ECCD at the q=2 surface. If the 2/1 mode does grow and rotationally lock, experiments have shown that it is possible to entrain the locked island in an externally imposed slowly rotating magnetic field generated by currents in non-axisymmetric coils inside the vacuum vessel. This process can be used to move the island O-point to a toroidal alignment consistent with the ECCD.

I. Introduction

The NTM is a magnetic island that is caused by a perturbation to the plasma current of the same helicity as the field line on a rational flux surface. The 2/1 NTM occurs at the minor radius where the safety factor q=2, which is close to the plasma boundary, so the interaction of the magnetic perturbation of the mode with induced eddy currents in the vacuum vessel leads to reduction of the plasma rotation, which in turn leads to mode locking and likely to a disruption. An estimate for ITER of the size of the 2/1 magnetic island that causes locking is 5 cm, only 2.5% of the minor radius [1]. Keeping the mode small or fully stabilized is therefore an important objective.

ECCD at the rational surface affects the NTM stability in two ways, by replacing the missing bootstrap current in an incipient or grown island and by modifying the classical stability parameter Δ' [2,3]. In this paper we present experiments on DIII-D in which the 2/1 NTM was completely avoided by early application of ECCD at the q=2 surface. These experiments show that the plasma β can be raised to at least the no-wall n=1 kink beta limit for many confinement times without the mode ever occurring. The second issue addressed is how to suppress NTMs that have grown to the extent that they rotationally lock to the vacuum vessel. This is an important issue for ITER because the 2/1 NTM may lock at small size due to the low rotation speeds. If the growing mode locks with a toroidal orientation that doesn't allow for application of ECCD at an island O-point, then the mode may not be controlled by ECCD. In experiments on DIII-D, non-axisymmetric coils have been used to apply magnetic fields to orient the NTM so that the ECCD suppression can be carried out.

II. Avoidance of the 2/1 NTM by Preemptive ECCD

The experiments on DIII-D on stabilizing or preventing the 2/1 NTM by means of ECCD at the q=2 surface were performed in hybrid discharges. The H-mode discharge has a single-null divertor configuration, with plasma current 1.2 MA, toroidal field B_T=1.5 T, q_{95}=3.9, and volume-averaged toroidal $\beta_T \approx 4\%$. The 110 GHz electron cyclotron heating (ECH) power is launched with X-mode polarization with the geometry of Fig. 1, which was chosen to facilitate movement of the location of the ECCD relative to the rational surface through small changes in the toroidal field under the control of the plasma control system (PCS). The total ECH power incident on the plasma from four gyrotrons is 2.4 MW, but about half the power is lost at the third harmonic.

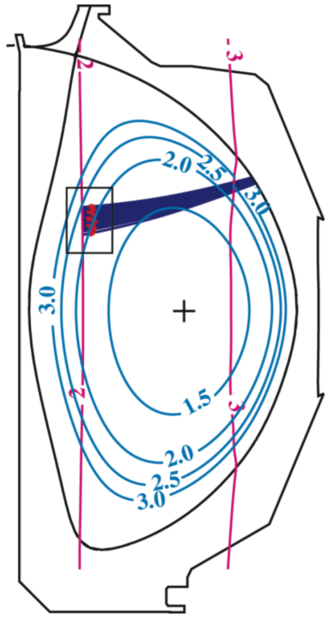

FIG. 1. (a) Cross-section of the DIII-D discharge showing the rational q surfaces. The rays of the EC beam are shown as the blue lines, and the magenta lines marked 2 and 3 are the second and third harmonics of the electron cyclotron resonance. Rational q-surfaces are shown.

Evolution of an example discharge showing prevention of the 2/1 NTM with β_N very near the stability limit is shown in Fig. 2. In this discharge, the EC power was applied at t = 4500 ms, while β_N was still rising [Fig. 2(e)]. The weak saturated n=2 mode that is characteristic of hybrid mode discharges appears earlier [Fig. 2(d)]. As β_N continues to increase, the PCS makes small adjustments to the toroidal field (not shown, Fig. 2) to maintain the current drive at the minor radius of the q=2 surface. The difference between the calculated minor radius of the current drive and the calculated q=2 radius was kept small compared to the radial width of the current drive layer. Good energy confinement was maintained and β_N was sustained for more than 1 s at the no-wall n=1 ideal kink stability limit of $\beta_T \approx 4.1\%$ and $\beta_N \approx 3.2$.

Many previous experiments on established NTMs have shown that precise positioning of the current driven by ECCD is crucial to successful suppression of the mode. In this experiment the mode is absent, but the accuracy of the placement of the ECCD is believed to be equally important. In these experiments this alignment of the ECCD with the rational surface is done by carrying out reconstructions of the equilibrium in real time, including information from the motional Stark effect diagnostic, which provides a profile of the safety factor q. The location in R and Z of the ECCD is calculated using the TORAY-GA code for an earlier discharge with similar properties, and the PCS calculates the change needed to B_T in order to bring the R of the peak ECCD into coincidence with the q=2 surface at the same Z. This closed-loop system is effective in keeping the ECCD aligned with its target surface as the plasma pressure is raised.

III. Magnetic Steering for Optimization of ECCD Control of Locked NTMs

In the experiments described above, the 2/1 NTM was avoided by using preemptive ECCD at the location of the mode. If this process were not successful at all times in a discharge, the mode may grow. In ITER, which will have low rotation rates because of the low applied torque, the mode would lock to the vacuum vessel while the island was still of very small size. If the ECCD applied to the growing island did not arrest the growth before the island reached about 5 cm in full width, the island may lock with a toroidal orientation which is not suitable for applying ECCD at the island O-point, given the toroidal location of the ECCD launcher. In this case the ECCD would be ineffective at reducing the island size.

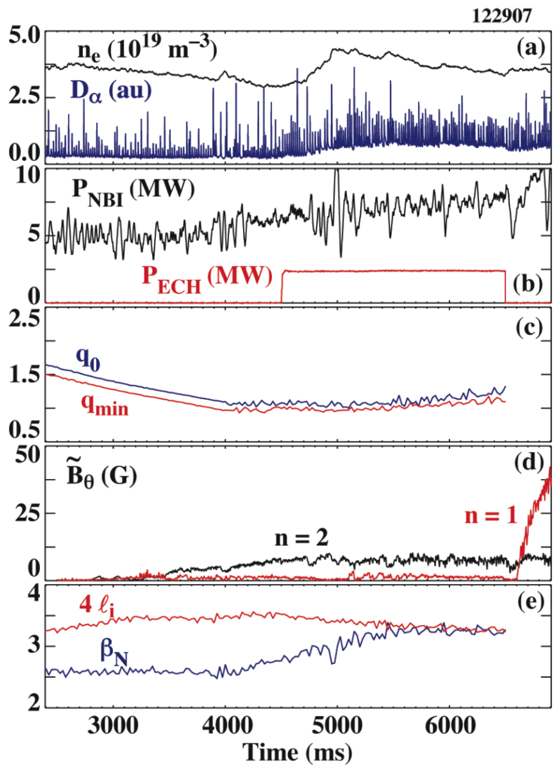

FIG. 2. Evolution of plasma behavior of a preemptive ECCD discharge. (a) line-averaged density and D_α emission, (b) EC power and time-averaged neutral beam power, (c) central and minimum value of safety factor q, (d) amplitudes of n=2 and n=1 tearing modes, measured at the outboard midplane wall, (e) normalized beta and four times the internal inductance (an estimate of the beta limit for the ideal n=1 kink mode in the absence of a conducting wall). Traces in (c) and (e) end where the motional Stark effect data stops.

This discrepancy between the location of the ECCD and the island O-point can be addressed by rotating the island to the toroidal location where the ECCD can be applied. DIII-D has non-axisymmetric coils inside the vacuum vessel (the I-coil [4]) that can be used for this purpose. These coils were wired to create a magnetic perturbation with the helicity of the magnetic island that rotates toroidally in the direction of plasma rotation. In the experiments, a 2/1 NTM was created by raising the β_N sufficiently high and the mode was allowed to grow until it began to lock. This can be seen in the traces of Fig. 3, in which the β_N rises until at about 3.2 it begins falling even though the NBI power is held constant. The falling frequency in Fig. 3(e) also indicates that the island is locking. At 2.2 s, when the mode frequency has dropped from 38 kHz to 8 kHz and is still dropping rapidly, the magnetic perturbation is turned on [Fig. 3(d)]. In this case, the radial magnetic perturbation is made to rotate toroidally at 0.66 Hz. The purpose of the rotation is to slowly rotate the island past the ECCD location to see the effect of changing the toroidal phase between the ECCD and the island after the ECCD is turned on, also at 2.2 s.

There is a toroidal array of saddle loops that can detect a radial magnetic perturbation. The signals from these sensors are used to determine the amplitude of the 2/1 magnetic island. This amplitude should not depend on its toroidal phase in the absence of ECCD, but in the presence of ECCD it is expected to vary depending on whether the ECCD is aligned with the O-point or not. For the case of Fig. 3, the amplitude varies from 4 to 7.5 G with an apparently regular phase dependence. The ECCD power was 1.3 MW, corresponding to two gyrotrons, which is known to be insufficient for full suppression of a rapidly rotating 2/1 NTM, hence modulation of the island amplitude rather than full elimination of the island is observed.

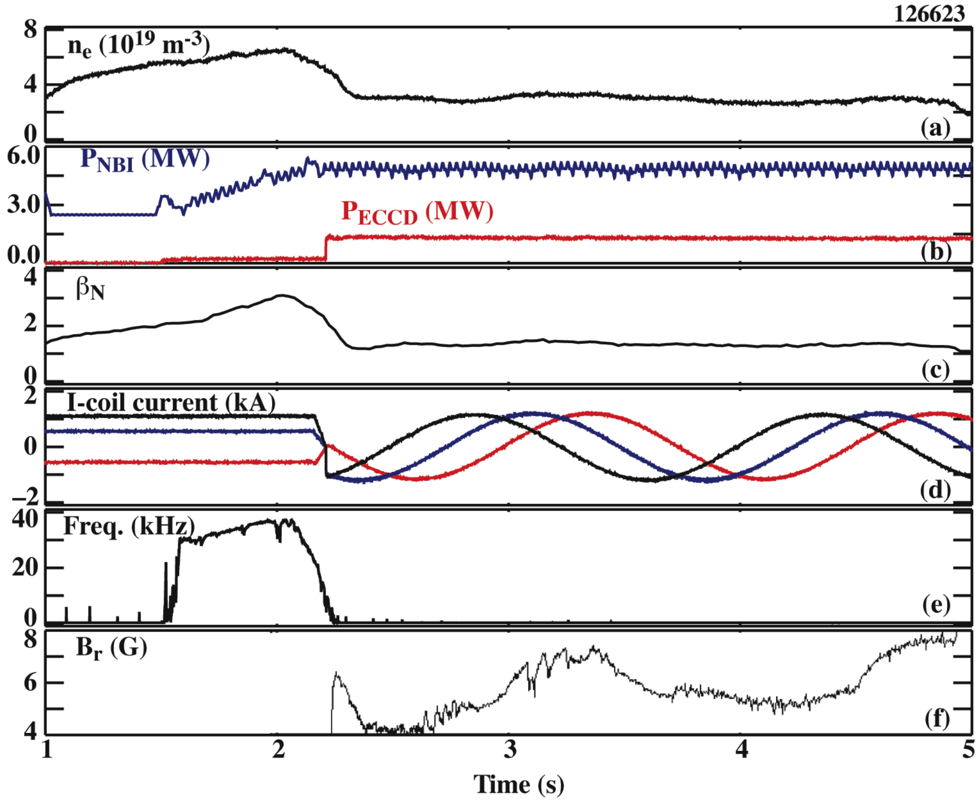

FIG. 3. Evolution of (a) density, (b) neutral beam and electron cyclotron current drive power, (c) β_N, (d) I-coil currents, (e) NTM mode frequency, and (f) radial magnetic field due to the magnetic island. Prior to 2.2 s, I-coil current is applied for error field control.

IV. Conclusions

Control of NTMs can lead to improved plasma performance, and ECCD has been shown to be an effective means of reducing or avoiding NTMs. Avoiding NTMs altogether has important advantages, the most important of which is that the mode will not lock and cause a strong loss of confinement or possibly a disruption. ECCD localized at the rational surface of the mode can avoid the modes up to at least the no-wall beta limit, but an accurate means of locating the rational surface in the absence of the mode must be used. In DIII-D experiments reconstruction of the equilibria in real time, including data from the MSE diagnostic, has been shown to be sufficiently accurate to keep the ECCD on target. If the NTM does grow, it may cause the plasma rotation to slow and lock. Experiments in DIII-D have demonstrated a promising technique to avoid locking by using externally applied magnetic perturbations. These perturbations move the NTM island to a toroidal location where ECCD can affect the mode, and some control of mode amplitude was found even at modest ECCD power.

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