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LOCKED NEOCLASSICAL TEARING MODE CONTROL ON DIII-D BY ELECTRON CYCLOTRON CURRENT DRIVE AND MAGNETIC PERTURBATIONS

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Locked Neoclassical Tearing Mode Control on DIII-D by Electron Cyclotron Current Drive and Magnetic Perturbations

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Abstract. Magnetic perturbations were used at DIII-D to unlock, reposition or spin locked tearing modes and so assist their electron cyclotron current drive (ECCD) stabilization. The applied rotation was considerably slower (0.66 Hz) or faster (up to 60 Hz) than the ECCD stabilization timescale of typically 100-200 ms. While the island was slowly dragged in the toroidal direction and illuminated by 1.3 MW ECCD, current was alternatively driven in its O-point and X-point. Correspondingly, a modulation of the mode amplitude by up to a factor 2 was observed by means of external saddle loops, consistent with the stabilizing/destabilizing effect of ECCD in the O/X point. Faster sustained rotation, at up to 60 Hz, was also demonstrated. This brings the locked mode case into the well-studied rotating neoclassical tearing mode (NTM) case. It also opens up the possibility to synchronize and phase-lock the mode rotation to the ECCD modulation, which is simpler than adapting the ECCD to the natural mode frequency and phase.

1. Introduction

Due to low torque neutral beam injection (NBI) only, it has been theoretically estimated that ITER plasmas will rotate at less than 1 kHz [1]. With the intrinsic rotation taken into account and extrapolated from present experimental results, this estimate might go up to 5 kHz [2]. Even so, rotation would be much lower than in present devices (5-40 kHz). As a result, NTMs will be less effectively shielded and be more prone to stop rotating and "lock" to the resistive wall or to the residual error field from imperfect error field correction. Rotating islands will lock even when they are relatively small (full width at half maximum w=5 cm in ITER, for an NTM of poloidal/toroidal mode number m/n=2/1 [3]). As a consequence of the relatively small size, rotating islands will have a smaller impact on the pressure profile. The main concern is the higher risk of locking and, thus, of disruptions.

Co-ECCD has proved effective in preventing NTMs, when applied before their onset, or completely suppressing them, if applied when they are still rotating. A good alignment of ECCD to the rational surface where the mode may form or has formed is known to be critical for both tasks. Moreover, the alignment needs to be preserved or adjusted in real time [4]. It is also important for the prevention or control to be timely, as the process of locking and disruption can take place rather rapidly after the mode onset [5]. The present paper addresses control strategies for when, due to late response or bad alignment, an NTM is not controlled on time and locks, or when it directly forms as a locked mode, without rotating precursor. In those cases, control by ECCD alone might pose difficulties, if the island locks with the O-point in a position not accessible by the steerable launchers or, worse, if current is driven in the X-point, with destabilizing effects. As an example, unless step-tunable gyrotrons will be adopted, there will be little control of ECCD in the horizontal direction in ITER, as alignment will mostly rely on steering. The upper launcher will be steered in one direction only, roughly vertical, and cover less than 25^o in the poloidal direction, as shown by ray tracing calculations in Fig. 1(a). This is insufficient to access the arbitrary 2/1 O-point, which can lock anywhere in a 180^o poloidal range. The system also lacks phase control in the toroidal direction, as the launchers cannot be toroidally steered and occupy four ports in a toroidal range of only 80^o. Therefore, a system of optical switches and beam combiners might direct the ECCD to a specific location within that 80° range, but would not cover the whole range of possible toroidal phases of 2/1 locking [360°, Fig. 1(b)].

In this paper it is shown that externally generated magnetic perturbations add flexibility to the ECCD control of locked modes, by either rotating the island to the toroidal location where the ECCD can be applied, or by keeping the island rotating.

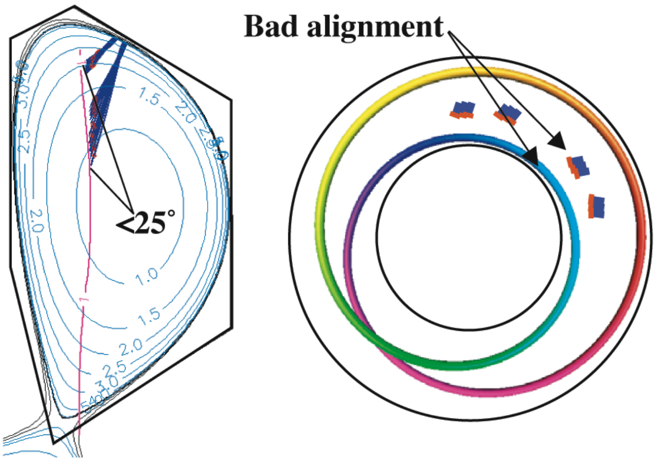

Fig. 1. (a) Poloidal projection of ray tracing results for ITER from the TORAY code, showing in red the lowermost and uppermost position where EC currents can be driven from the upper launcher, spanning a poloidal angle interval of less than 25°. (b) Top view of gyrotron beams launched from ITER upper launchers, and 2/1 mode locked with an unfavorable toroidal phase. The colored curve is the 2D projection of the 2/1 island O-point.

2. Experimental Setup and Discharge Description

DIII-D is equipped with six non-axisymmetric coils outside the vacuum vessel, in the equatorial plane (the C-coils) and 12 coils inside the vessel, above and below the midplane (the I-coils). The C- and I-coils have been used for error field correction, and for the stabilization of resistive wall modes and edge-localized modes.

In the present locked mode experiments, the six upper and six lower I-coils were wired to produce a helical field with a pitch approximating that of the 2/1 magnetic island and with the same n=1 periodicity. The coil currents create a radial magnetic field and, by applying an alternating current with 60° phase difference between adjacent coils, a magnetic perturbation that rotates toroidally in the direction of the plasma rotation can be made. At the same time, the error field was corrected by means of the C-coils. This is important because dragging the island in the presence of a residual error field would modulate its amplitude, whereas here we want to isolate the effect of ECCD.

In both experiments, a 2/1 NTM is created by raising the NBI power [Fig. 2(a)] and, thus, the normalized beta sufficiently high [Fig. 2(b)]. By increasing β_N, the mode is excited [Fig. 2(c)] and interacts more and more with the wall and residual error field until it begins to lock, as the falling frequency in Fig. 2(d) indicates. As a result, β_N decreases, despite the NBI power being held constant, and the confinement degrades, as it is visible from the density decrease in Fig. 2(e).

Mode locking is detected in real time by three main diagnostics. One of these is the toroidal array of Mirnov coils, measuring the growth rate of the n=1 poloidal field: large growth rates, of 20 T/s at DIII-D, generally indicate imminent locking. When a single mode is dominant, a frequency counter connected to the Mirnov coils provides a measure of its frequency. Mirnov coils are sensitive to fast fluctuations, >100 Hz, and detect the rapidly growing, rapidly slowing-down rotating precursor of a locked mode. A third diagnostic, a set of external saddle loops, measures the dc or slowly varying (<100 Hz) radial field and is suitable for the detection of locked modes with no rotating precursors.

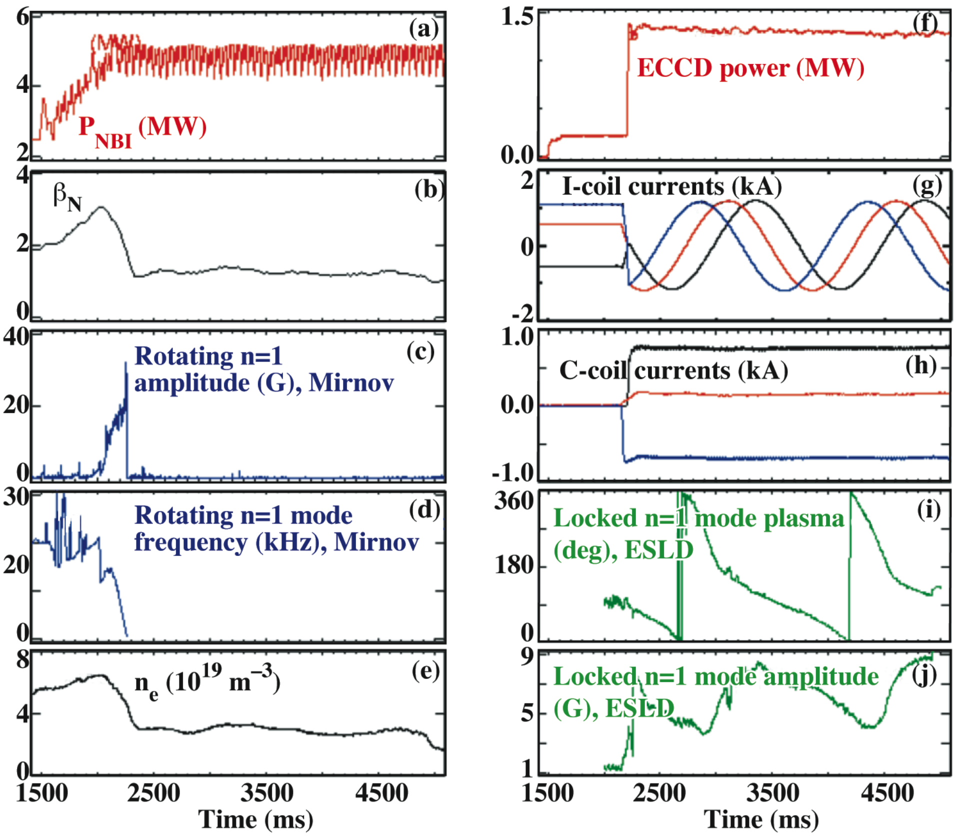

Fig. 2. Evolution of (a) NBI power, (b) β_N, (c) rotating n=1 growth rate and (d) frequency, (e) density, (f) ECCD power, (g) I-coil and (h) C-coil currents, (i) phase and (j) radial field amplitude of locked n=1 mode.

As soon as one of these sensors detects a locked mode or its rotating precursor, the ECCD is turned on [Fig. 2(f)] and a rotating field is applied from the I-coils [Fig. 2(g)]. The error field correction, previously operated by the I-coils, is then handed to the C-coils [Fig. 2(h)]. Experiments of the two types share the same early part of the discharge, where the mode is triggered and locks, but differ in the rotating field applied for its control.

3. Slow Entrainment and cw ECCD Results

The first approach consists in toroidally rotating the island to the location where ECCD is driven in its O-point. Here, however, for the sake of comparison of ECCD in the O- and X-point, the island was rotated even beyond the O-point, for two complete toroidal revolutions [Fig. 2(i)]. In this way, current was alternatively driven in the O- or X-point within the same discharge. The rotation was slow enough (0.66 Hz) to allow the stabilizing/destabilizing effects of the ECCD to become visible [Fig. 2(j)]. From naturally rotating NTM experiments, the time-scale for ECCD stabilization is known to amount to some hundreds of ms at DIII-D.

An array of saddle loops was used to measure the radial magnetic field associated with the island. The toroidal orientation was inferred and, for example, it was confirmed that the island was dragged by the external perturbation. The mode amplitude was also inferred from the saddle loop measurements. This amplitude should not depend on its toroidal phase in the absence of ECCD, but in its presence it is expected to vary depending on whether the ECCD is aligned with the O-point or not. For the case of Fig. 2(j), the amplitude varies from 4 to 7.5 G with an apparently regular phase dependence. The ECCD power was 1.3 MW, from two gyrotrons, which is known to be marginal 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.

A number of checks were carried out to verify that the measured mode amplitude is correctly determined as due to a magnetic island. First, measurements similar to those shown in Fig. 2 were made without a plasma present. In contrast to Fig. 2(j), the apparent mode had an amplitude of about 1 G and rotated uniformly. This vacuum measurement was indeed the measurement, by the saddle loops, of the perturbation applied by the I-coils, confirming that the applied perturbation was constant in amplitude and uniform in rotation. Hence, the amplitude modulation observed in Fig. 2(j) cannot be ascribed to instrumental effects such as a misalignment between the perturbing and diagnostic coils. When the reference signal is subtracted from the data of Fig. 2(j), the locked mode still changes amplitude regularly when the toroidal phase is swept. As a second check, the radial location of the ECCD was moved away from the minor radius of the island by lowering the plasma current and the toroidal field by 3%, so that the heating, plasma pressure, density profile, and interaction of the mode with the error field would be the same but the interaction of the ECCD with the island should be avoided. In this case, the island is larger but there is negligible correlation of the size with the toroidal phase, indicating that the phase modulation of the island size shown in Fig. 2(j) is due to the ECCD. This experiment would be clearer with sufficient ECCD power to fully eliminate the island, but higher power was not available at the time of this experiment.

4. Fast Entrainment Results

The second approach of keeping the island rotating by means of a rapidly rotating magnetic field, if successful, reduces the island control problem to the previously well-studied case of a rotating island with constant or modulated ECCD. If the island can then be suppressed, the rotational locking may be eliminated and the plasma may heal itself without further intervention. Furthermore, the entrainment opens up the possibility to synchronize and phase-lock the mode rotation to the ECCD modulation, which is simpler than adapting the ECCD to the time-varying natural mode frequency and phase. As shown below, the entrainment has also a potential as a control method by itself, as it rotationally mitigates the mode, and a diagnostic potential, as it allows diagnostics to resolve the spatial structure of the island as it moves in front of them at a controlled velocity, amenable to their temporal resolution.

These initial experiments focused on making a stationary plasma to rotate. For the fast entrainment case, the ECCD stabilization of NTMs was not yet tested. It was found that if the rotating perturbation started out at low frequency, around 1 Hz, and was ramped over a 1.5 s period to 60 Hz, then it could be successfully entrained to the initially locked mode, and sustain its rotation (Fig. 3, after a “vacuum shot” subtraction similar to Sec. 3). Note that, for the same I-coil current, the perturbation in the plasma gets smaller as the frequency rises, due to partial cancellation from image currents in the wall.

Figure 3 also show that the mode is suddenly and strongly mitigated, from ~10 G to ~2 G, when its rotation frequency exceeds ~10 Hz.

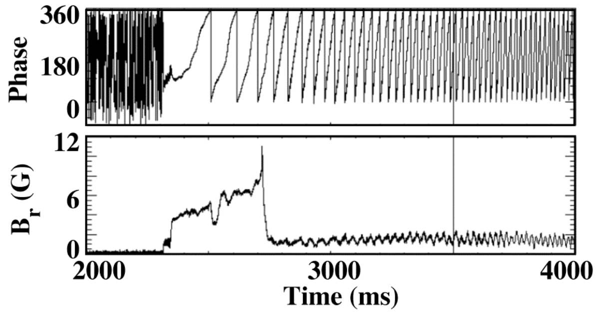

Fig. 3. Phase and amplitude of an NTM initially locked to the wall, unlocked at t=2300 ms and forced to rotate by an I-coil traveling wave accelerating from 1 to 60 Hz.

5. Summary and Conclusions

NTMs in ITER are expected to initially rotate very slowly and thus be prone to stop rotating and "lock" to the resistive wall and error field. They can lock with a toroidal phase such that they cannot necessarily be accessed and suppressed by ECCD. New techniques where ECCD is assisted by magnetic perturbations exerted by the internal I-coils were tested at DIII-D.

In the first type of experiment, magnetic perturbations were used to steer the mode and lock it with a new phase such that it could be stabilized by ECCD. Mitigation of the locked NTM was obtained with this technique with 1.3 MW of ECCD power. Future work in this area includes the repetition of the experiment with more ECCD power (>2.4 MW). Modeling suggests that 3 MW would completely suppress the island.

In the second class of experiments, rotating fields unlocked the mode and sustained its rotation at up to ~60 Hz. A sudden mode mitigation was observed at ~10 Hz. For complete stabilization, the entrainment will be repeated with ECCD, both cw and modulated. Modulation will be at the controlled rotation frequency and phase. This is expected to be easier than adapting the ECCD to the naturally rotating mode.

Future work will also explore pre-emptive control, which has the promise for complete locked mode avoidance. A recently developed detector of rotating precursors based on real-time FFT analysis of Mirnov signals will be used for this purpose. It has the advantages, over the frequency counter, of being less noisy and being mode-selective.

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