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CONTROL OF NEOCLASSICAL TEARING MODES FOR IMPROVED PERFORMANCE IN ITER

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ABSTRACT

Control of neoclassical tearing modes (NTMs) in the ITER tokamak may be needed for operation in many high performance scenarios. Electron cyclotron current drive (ECCD) has been shown to be effective in stabilizing the toroidally rotating modes when the ECCD is localized near the location of the NTM. On DIII-D, NTMs have been avoided altogether by pre-emptively applying ECCD in the correct location, as inferred from equilibria reconstructed in real time, and the plasma pressure was raised to the kink mode stability limit with β near 4.0% without the occurrence of the mode. In ITER, plasmas are expected to rotate more slowly, and the interaction of low-order NTMs with the vacuum vessel can cause the rotation to lock even for small island size. If this happens, the magnetic structure of the island may not be oriented toroidally for effective control by ECCD. This is being addressed on DIII-D by use of magnetic perturbation fields generated by non-axisymmetric coils inside the vacuum vessel to entrain the islands and keep them rotating or to move them to a toroidal location where the ECCD can be effective.

I. INTRODUCTION

High fusion gain in a tokamak requires operation near the pressure limit for stability. One instability which places a limit on the pressure is the neoclassical tearing mode. This mode may arise when the normalized plasma pressure [$\beta_N \equiv \beta/(I_{MA}/a_m B_T)$, where I_{MA} is the plasma current in MA, a_m is the minor radius in meters, and B_T is the magnetic field in Tesla] exceeds a critical value. For ITER this critical beta is calculated to be significantly lower than the operating point of 1.8. Relief from the lower beta limit will permit higher performance operation in ITER.

The NTM (for review see Ref. [1]) 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. Fully grown NTMs with $m = 3$ and $n = 2$ degrade the energy confinement by typically 10% to 30%, while modes with $m = 2/n = 1$ lead to severe energy loss and frequently to disruption if rotational locking takes place. The 2/1 mode 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 [2]. 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 [3]. Keeping the mode small or fully stabilized is therefore an important objective.

Electron cyclotron current drive (ECCD) has been shown in several experiments on tokamaks to be effective in stabilizing rotating 3/2 and 2/1 NTMs. In those experiments an NTM of fully saturated island size was suppressed by the ECCD. In the case of the 3/2 NTM, it was shown that this stabilization leads to operation at increased β [4,5]. This work has generally shown good agreement with theory including the effect of the ECCD on the classical tearing stability [6]. The very narrow current drive profiles characteristic of ECCD in DIII-D [7], typically 3 cm full width half maximum (FWHM) are well-suited for stabilizing NTMs and the spatial precision of the placement relative to the rational surface is required to be of order 1 cm. Correct placement of the ECCD in the island was facilitated in the experiments on DIII-D by a feedback-controlled search technique to find and maintain the current drive location that minimizes the mode amplitude [8].

The ECCD affects the NTM stability in two ways. When the mode exists, the island flattens the plasma pressure, so that the bootstrap current which is generated by the radial pressure gradient decreases within the island. This decrease causes a magnetic perturbation which is destabilizing. One effect of the ECCD is to drive a helical current within the island which compensates for the decrease in bootstrap current, improving stability. A second effect is to modify the classical stability parameter [9,10]. Experiments applying ECCD before the onset of the mode to modify (and to replace the perturbed bootstrap current in incipient islands) on JT-60U showed that the 3/2 mode could be avoided using less EC power than that which was required to stabilize the mode from its fully saturated state [11], but increased plasma pressure subsequent to the disappearance of the mode was not demonstrated in those experiments. Experiments on the preemptive stabilization of the 3/2 mode in DIII-D showed that higher stable β could be achieved [5].

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. This work is motivated by the observation that the process of mode locking and disruption can take place rather rapidly and at rather small island size [2]. In order to avoid the disruption which may follow the mode locking, it is preferable to avoid the 2/1 NTM entirely rather than to suppress the mode after it has grown to observable size. This is more difficult than for the 3/2 mode due to less effective current drive at the larger minor radius and to the larger growth rate of the 2/1 NTM. 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 rotationally locked to the vacuum vessel. This is an important issue for ITER because the 2/1 NTM will lock at small size due to the low rotation speeds. If the growing mode locks with a toroidal orientation that does not allow for application of ECCD at an island O-point, then the mode may not be stabilized. In experiments on DIII-D, non-axisymmetric coils have been used to apply magnetic fields to orient the NTM so that the ECCD interaction can be carried out constructively or to keep the mode rotating so that cw ECCD can reduce the mode amplitude.

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 mode” discharges [12,13]. The hybrid mode is characterized by the presence of a small, rather benign, 3/2 NTM which acts to limit the central peaking of the current density profile but which is of sufficiently small size that the small confinement penalty is acceptable. By this means, the profile of current density is broadened, the sawtooth instability is avoided, and improved performance is found.

In the subject discharges, the 2/1 NTM is controlled by application of ECCD at the rational surface. The H-mode discharge has a single-null divertor configuration illustrated in Fig. 1, with plasma current 1.2 MA, toroidal field 1.5 T, $q_{95} = 3.9$, and volume-averaged toroidal $\beta \approx 4\%$. The 110 GHz electron cyclotron heating (ECH) power is launched with X-mode polarization from a port above the midplane, and the second and third harmonics of the electron cyclotron resonance are shown in the figure. The total ECH power incident on the plasma from four gyrotrons is 2.4 MW. The EC power is launched with a toroidal angle of 14 deg from radial in a compromise between maximum ECCD (large toroidal angle) and minimum profile width (small toroidal angle) [4,14]. For these conditions, the full width δ_{ec} at half maximum of the ECCD profile is about 5% of the minor radius, or ~3 cm. The time-averaged neutral beam injection (NBI) power is under real-time control of the Plasma Control System (PCS) using a feedback system to keep the plasma β near a pre-programmed trajectory in time.

The radial profiles are shown in Fig. 2. The EC quantities are calculated by the TORAY-GA ray tracing code [15]. Figure 1 shows that there is observable refraction of the EC waves away from the center of the plasma. Moderate refraction is expected since the electron density of $4 \times 10^{19}\,\mathrm{m}^{-3}$ at the minimum minor radius of the waves, about $\rho = 0.5$, is not small compared to the X-mode cutoff density of $6.4 \times 10^{19}\,\mathrm{m}^{-3}$ for 110 GHz and the value of the parallel index of refraction ($n_{\|} = 0.35$) there.

The geometry of Fig. 1 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 PCS. Increasing B_{T} increases the major radius of the second harmonic resonance, moving the ECCD to smaller minor radius. The third harmonic lies well inside the plasma, and approximately 60% the EC power is calculated to be lost there parasitically. Current drive by the third harmonic power is negligible because the resonant interaction is almost entirely with deeply trapped electrons. The loss of power at the third harmonic is considered when the ECCD is calculated for the second harmonic. Given the conditions of density ($3.4 \times 10^{19}\,\mathrm{m}^{-3}$) and electron temperature (2.3 keV) at the location of the ECCD, and the power lost at the third harmonic, the driven current is 16 kA and the peak driven current density is 12.2 A/cm^2, compared to the calculated bootstrap current density of 17.1 A/cm^2 and equilibrium current density of 75 A/cm^2 at the time analyzed for Fig. 2 (6315 ms).

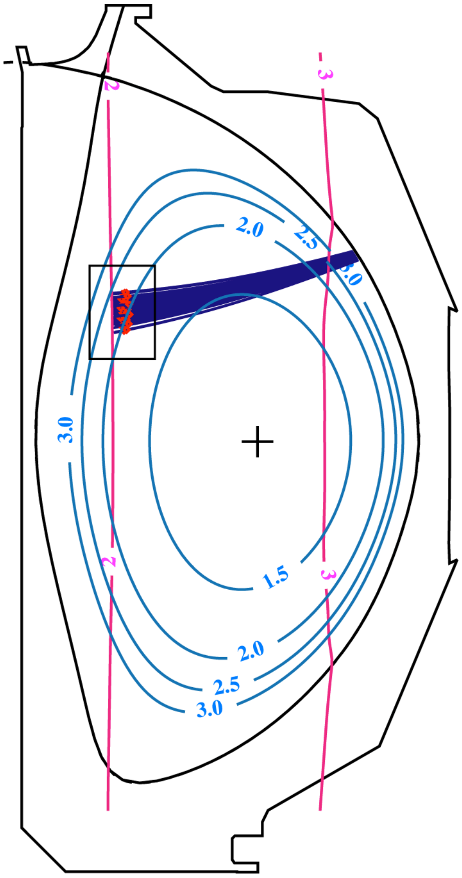

Fig. 1. (a) Cross-section of the DIII-D discharge showing the rational q surfaces. The rays of the EC beam are shown as the blue lines, and the magenta lines marked 2 and 3 are the second and third harmonics of the electron cyclotron resonance. Rational q-surfaces are shown.

The evolution of an example discharge showing prevention of the 2/1 NTM with β very near the stability limit is shown in Fig. 3. In this discharge, the EC power was applied at t = 4500 ms, while β was still rising [Fig. 3(e)]. The saturated $n = 2$ mode that is characteristic of hybrid mode discharges appears earlier [Fig. 3(d)]. As β continues to increase, the PCS makes small adjustments to the toroidal field (not shown in Fig. 3) 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 one second at the no-wall $n = 1$ ideal kink stability limit of $\beta_T \approx$ 4.1% and $\beta_N \approx$ 3.2. The estimate of the no-wall limit shown in Fig. 3(e) as $\beta_N \approx 4\,\ell_i$, with ℓ_i the internal inductance of the plasma, agrees with ideal stability calculations to within about 10%. (Plasma rotation may allow the vacuum vessel wall to stabilize the kink mode at or beyond the no-wall limit, but this was not tested in these experiments.) When the ECCD is turned off at t = 6500 ms, the NBI is programmed to maintain β at the same value. The onset of a 2/1 NTM about 100 ms later, Fig. 3(d), shows that the presence of the ECCD was necessary for the stability of the plasma. This was also clearly seen in comparable discharges without ECCD. Since the ECCD is applied at a rather large minor radius, the heat is not well confined, and the EC power reduces the normalized confinement time H_{89} from 2.35 to 2.0 if it is included in the total heating power. Here, the ECCD is used to increase the stability limit rather than for heating and confinement.

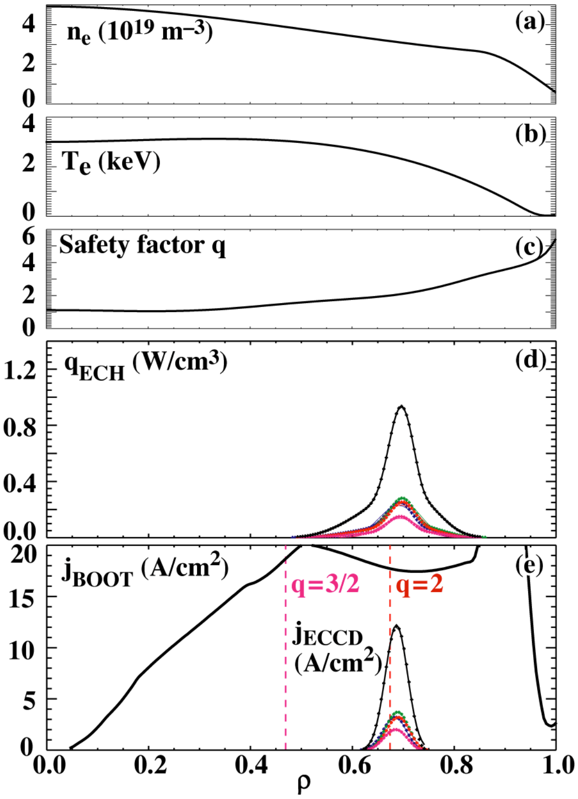

Fig. 2. Profiles as a function of normalized minor radius ρ. (a) Plasma density, (b) electron temperature, (c) safety factor q, (d) power density due to EC wave absorption, and (e) ECCD current density profile for each of the four EC systems (colored) and the total (black) and, for comparison, the bootstrap current density profile. Profiles are taken at 6315 ms for shot 122907.

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 the work on fully grown NTMs, the effects of the continuous co-ECCD very near the rational surface are to replace the loss of the bootstrap current within the island due to the flattening of the pressure gradient within the island and to increase the classical stability (that is, make Δ' more negative). In these experiments only the latter process is in effect when islands are not present. However, the coupling to edge localized modes (ELMs) or the higher order components of the 3/2 mode (the 4/2 harmonic of the 2/1 mode can toroidally couple to the 3/2 mode) can generate small islands, so replacing the missing bootstrap current is kept in the modeling of the pre-emptive control. From a theoretical point of view, this experiment is somewhat cleaner than the case with substantial islands, since the effect of the islands on broadening the effective ECCD profile need not be considered. Also, the coupling between modes which has been observed on DIII-D to cause frequency locking between the $m=3/n=2$ mode at the $q=3/2$ surface and the 2/1 mode at the $q=2$ surface is avoided. Finally, the change in Δ' due to the presence of an island need not be considered.

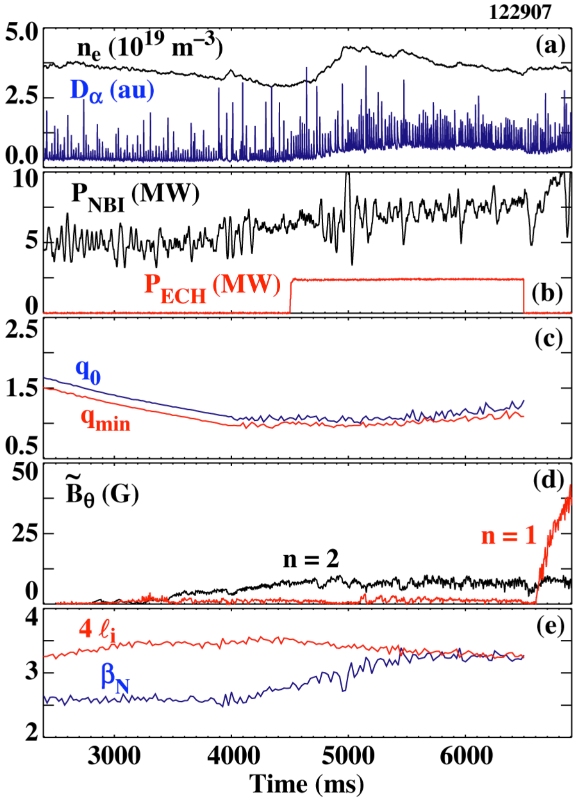

Fig. 3. Evolution of plasma behavior of a preemptive ECCD discharge. (a) line-averaged density and D_α emission, (b) EC power and time-averaged neutral beam power, (c) central and minimum value of safety factor q, (d) amplitudes of $n=2$ and $n=1$ tearing modes, measured at the outboard midplane wall, (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.

The key problems in devising a closed-loop feedback control system to keep the ECCD on the $q=2$ flux surface are identifying the location of the rational surface in real space and determining the location of the peak of the ECCD. In these experiments this is done by carrying out reconstructions of the equilibrium in real time, which provides a profile of the safety factor q. The real-time equilibrium reconstructions [16] are carried out by the PCS using information from 16 internal poloidal field measurements from the motional Stark effect (MSE) diagnostic [17], as well as a large number of magnetic measurements outside the plasma (39 flux loops, 31 poloidal field probes, all shaping coil currents, and a Rogowski coil). The real-time EFIT algorithm obtains a solution to the Grad-Shafranov equation that minimizes the differences between the input signals and the equilibrium. The time required to obtain an equilibrium is about 6 ms, and the solutions obtained are very close to those obtained off-line using the EFIT code with the same input data. However, not as much filtering of the inputs is performed for the real time EFITs as for off-line EFITS, so the results contain a little more scatter. 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. The response time of the toroidal field to the PCS command is about 100 ms. This closed-loop system is effective in keeping the ECCD aligned with its target surface as the plasma pressure is raised. For some discharges, the toroidal field could be successfully pre-programmed after substantial trial and error, but the result is much less robust. The closed-loop system is much more effective in maintaining correct alignment over a range of conditions.

III. Magnetic steering for optimization of ECCD control

In the experiments described above, the 2/1 NTM was avoided by using pre-emptive ECCD at the location of the mode. If this process were not successful at all times in a discharge, the mode would 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 rotating 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 restraining further growth of the island.

Two ways of addressing this discrepancy between the location of the ECCD and the island O-point are to either rotate the island to the toroidal location where the ECCD can be applied or to keep the island rotating. DIII-D has non-axisymmetric coils inside the vacuum vessel (the I-coil) which can be used for these purposes [18]. The 12 independently powered coils are arranged as shown in Fig. 4. In this experiment, the six upper coils and six lower coils were wired to produce a helical field with a pitch approximating that of the magentic island. The coil currents create a radial magnetic field, and by applying an alternating current with 60 deg phase difference between adjacent coils, a magnetic perturbation that rotates toroidally in the direction of the plasma rotation can be made.

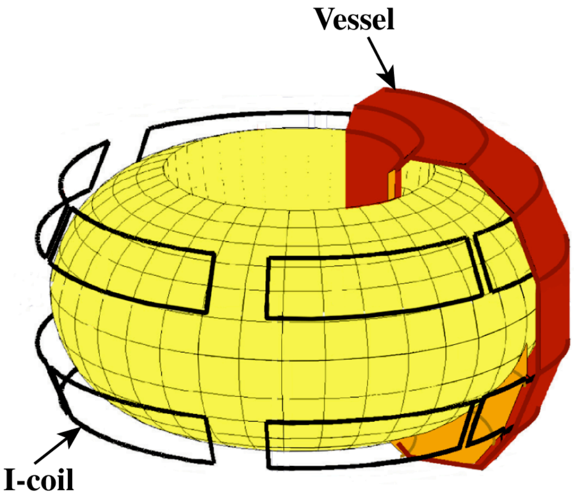

Fig. 4. DIII-D plasma surface, showing cut-away vacuum vessel and the internal I-coil segments lying inside the vessel.

In the first set of experiments, a 2/1 NTM was created by raising the normalized beta sufficiently high, and the mode was allowed to grow until it began to lock. This can be seen in the traces of Fig. 5, 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. 5(e) also indicates that the island is locking. At 2.2 s, when the mode frequency has dropped from 38 to

8 kHz and is still dropping rapidly, the magnetic perturbation is turned on, as shown in Fig. 5(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. 5, 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.

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. 5 were made without a plasma present. In contrast to Fig. 5(f), the apparent mode amplitude was about 1 G and constant in phase. When this signal is subtracted from the data of Fig. 5(f), the locked mode still changes amplitude regularly when the toroidal phase is swept. Second, 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 modulation of the island size shown in Fig. 5(f) is due to the ECCD. This result would be clearer with sufficient ECCD power to fully eliminate the island, but higher power was not available at the time of this experiment. Nevertheless, the experiments appear promising.

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. These initial experiments focused on making a stationary plasma to rotate. It was found that if the rotating perturbation started out at low frequency, around 1 Hz, the frequency could be ramped over a 1.5 s period to 60 Hz, with the plasma successfully entrained. Higher frequencies were not obtained, as the current in the I-coil falls off with frequency, and even for the same I-coil current the perturbation in the plasma is smaller as the frequency rises due to the image currents in the wall, which increase in amplitude as the frequency increases. For the entrainment case, the ECCD stabilization of NTMs was not yet tested.

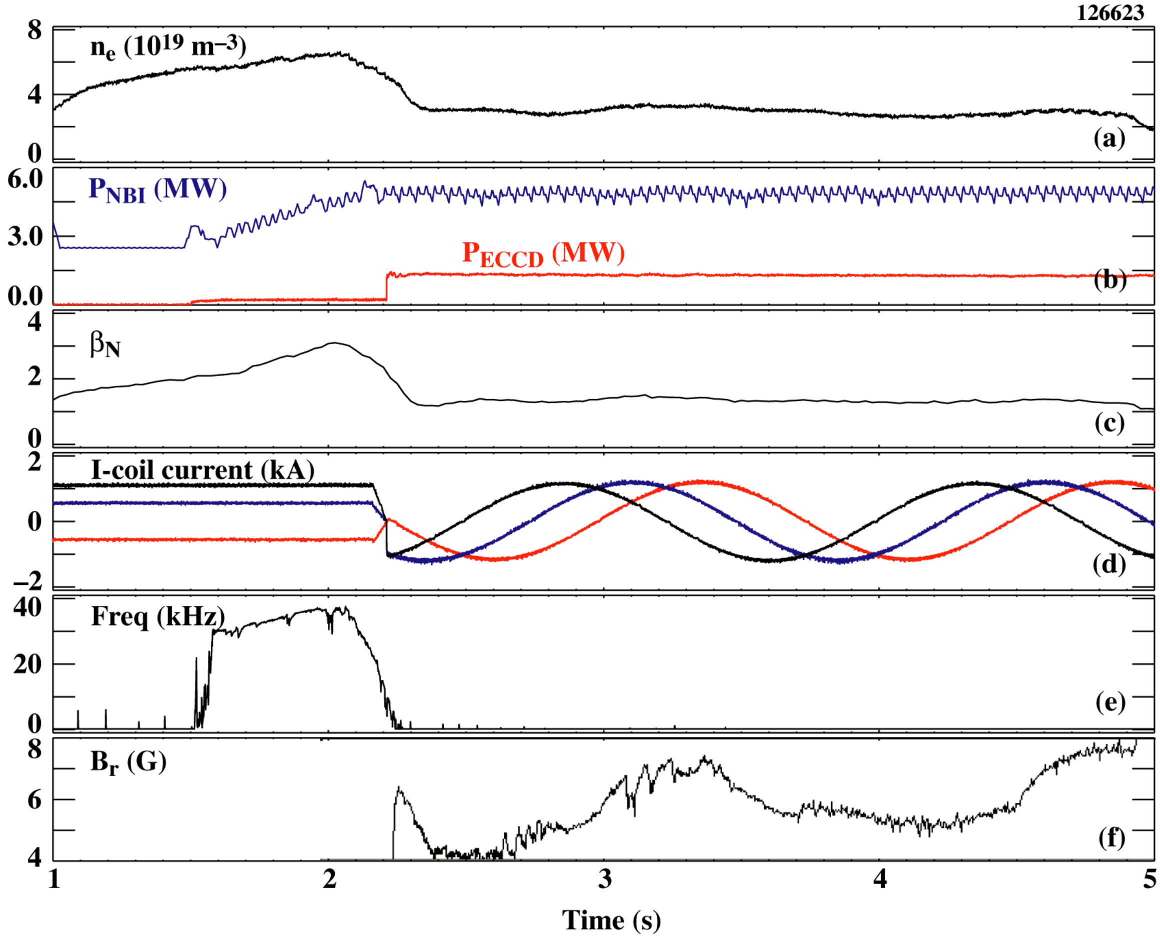

Fig. 5. Evolution of (a) density, (b) neutral beam and electron cyclotron current drive power, (c) β_N, (d) I-coil currents, (e) NTM mode frequency, and (f) radial magnetic field due to the magnetic island.

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, for some reason, the NTM begins growing, it may cause the plasma rotation to lock, particularly in a low-rotation plasma like that expected in ITER. Preliminary experiments in DIII-D have demonstrated a promising technique to avoid locking by using rotating externally applied magnetic perturbation. These perturbations may either move the NTM island to a toroidal location where ECCD can stabilize the mode, or the perturbations may be used to keep the island rotating at a modest speed. In the latter case, the ECCD may be expected to stabilize the mode just as in experiments on modes that rotate rapidly naturally.

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