Development of robust and multi-mode control of tearing in DIII-D

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***Abstract*—Neoclassical tearing modes (NTMs) are instabilities that can produce undesirable magnetic islands in tokamak plasmas. They can be stabilized by applying electron cyclotron current drive (ECCD) at the island. The NTM control system on DIII-D can now control multiple modes. Each of 6 mirrors that reflect ECCD beams into the plasma can be assigned to different surfaces in the plasma where NTMs are unstable. The control system then steers the mirrors to keep the beams aimed at the surfaces. The system routinely stabilizes one NTM preemptively and has now also been used to control two modes in the same discharge.**

With the "catch-and-subdue" function, ECCD-generating gyrotrons can be turned on when NTMs appear and off after suppression. Newly triggered NTMs can be promptly suppressed if mode onset is detected early and ECCD immediately applied. Early mode detection is achieved by spectral analysis of Mirnov probes with a band-pass filter for the expected mode frequency. Targeted surfaces are tracked by equilibrium reconstructions (that include measurements of the motional Stark effect). The ECCD position is tracked by ray-tracing using the TORBEAM code.

Several techniques are being explored for fine-tuning alignment when NTMs occur. One method adjusts ECCD alignment in steps until the island decays fast enough. A second method sweeps the alignment to find the optimum. A third method pulses gyrotrons and uses electron cyclotron emission to compare where the resulting temperature pulses are relative to temperature fluctuations from a rotating NTM. NTM control in ITER is expected to use active profile regulation to maximize controllability, followed by repeated catch-and-subdue actions if modes are retriggered, in order to maintain island size below the disruptive threshold while maximizing confinement and fusion gain. Between events, real-time tracking will be performed to maintain alignment and readiness for subsequent catch-and-subdue actions. Methods for active probing of stability boundaries will be studied as possible diagnostics for the profile regulation. Selected elements of this ITER NTM control vision will be discussed and assessed.

Keywords—plasma control; tokamak; NTM

I. Introduction

The tearing mode (TM) is a magnetic island caused by a helical perturbation to the plasma current of the same helicity as the field lines on a flux surface where q=m/n is a rational number, with m being the poloidal mode number and n the toroidal. The neoclassical tearing mode (NTM) is a TM which is linearly stable but can be destabilized if the island size is excited above a threshold by a seeding mechanism. It then grows to a saturated size. Saturated NTM islands with m/n=3/2 degrade the energy confinement by typically 10%–30%, while modes with m/n=2/1 lead to severe energy loss and frequently to disruption [1]. Evidence from experiments and numerical simulations show that, without control, ITER will have unstable 2/1 islands. The results suggest that growth of a 2/1 island will produce a loss of H-mode, then lock to the wall and lead to a disruption. Hence, suppression of tearing modes will be essential for ITER. Tearing modes can be stabilized by driving current at the resonant surface. This increases linear stability and replaces the missing bootstrap current. A good figure of merit for a TM control actuator is how much current density can be driven at the resonant surface. Gyrotrons are a good choice because the electron cyclotron current drive (ECCD) is concentrated to a narrow region that therefore has the desired high current density [2]. However, since the alignment error must be less than the width of the region (typically small relative to the minor radius), this means that the ECCD must be aligned very accurately with the resonant surface. The purpose of the NTM control system in DIII-D is to explore NTM physics and develop techniques of interest for ITER and beyond as well as serving as a tool for experiments that need NTM suppression. Hardware and basic control functions are described in section 2. The actuators can be used both for current profile control and for NTM suppression and the two objectives will become tightly integrated. The real time data analysis needed for a fully-integrated control system is expected to be challenging. Section 3 describes analysis that has already been implemented for DIII-D and is applicable to both current profile control and NTM control. Section 4 deals with robust alignment techniques; these can be viewed as part of the data analysis but are only used for NTM control. The first control of two NTMs in the same discharge is described in section 5. Section 6 describes the catch and subdue function that saves average gyrotron power by turning gyrotrons off when NTMs have been stabilized. Section 7 outlines a control vision for ITER where the different elements come together into a larger control function. Concluding remarks are in section 8.

II. HARDWARE FOR NTM AND PLASMA PROFILE CONTROL

For the 2015 campaign DIII-D has 6 gyrotrons that can be used for control of tearing modes. The beams from each of the gyrotrons are reflected into the plasma by mirrors that can be steered in real time to control where the power from the beams is absorbed. Absorption occurs at the EC resonance, which is an almost vertical line along which the frequency of the EC radiation equals twice the gyro frequency of the electrons in the plasma. Adjusting the mirror angle therefore amounts to moving the deposition point up and down along the resonance line. Fig. 1 shows the scheme for one of the gyrotrons. For NTM control, the system keeps the deposition point on the NTM resonant q-surface shown in blue and turns on the gyrotrons as quickly as possible after an NTM has been triggered or keeps the gyrotrons on at all times. The control system can control each of the 6 mirrors and 6 gyrotrons individually and assign different tasks for each. Mirrors can be controlled by three kinds of targets: angle, rho, q. In the first case the mirror simply moves according to preprogrammed angles. In the second case the mirror moves in order to deposit the power at a preprogrammed minor radius (rho) inside the plasma. In the third case the mirror moves to deposit the power at preprogrammed q-surfaces. This last option is used for NTM control. More details regarding NTM control hardware are available in [3].

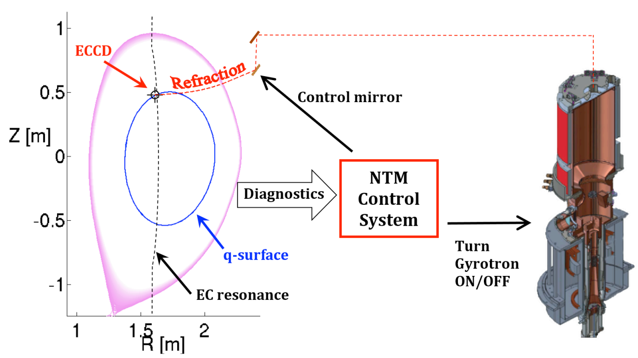

Fig. 1. The NTM control system analyzes diagnostics to detect NTMs and find positions of ECCD and q-surfaces. The beams from the gyrotrons are reflected by focusing mirrors and controlled steerable mirrors into the plasma where they are refracted by the plasma and absorbed at the EC resonance line to produce ECCD. The mirrors are typically controlled even when the gyrotrons are off so that the ECCD will be immediately aligned when the gyrotrons are turned on.

III. REAL-TIME ANALYSIS FOR NTM & PROFILE CONTROL

The DIII-D control system uses a real-time version of the MHD equilibrium reconstruction code EFIT [4]. The equilibrium reconstructions are based on external measurements made by flux loops, low frequency Mirnov probes and a Rogowski coil, and on internal measurements of the motional Stark effect (MSE). The MSE diagnostic gives the field line pitch at points inside the plasma and helps constrain the equilibrium reconstructions so that the resulting q-profile is sufficiently accurate for tracking changes to the q-surface. A set of high frequency Mirnov probes can be used to infer sizes of magnetic islands based on field fluctuations caused by rotation of the islands. Refraction of the beams is calculated by the real-time ray tracing code TORBEAM based on density profiles from Thomson scattering [5].

IV. ALIGNMENT TECHNIQUES

Developing techniques for good alignment of ECCD to the q-surface received early attention in the DIII-D program since they are crucial for NTM suppression [6].

An algorithm called “Active Tracking” is always on during NTM control whether an NTM is present or not. This algorithm makes the ECCD track a specified q-surface by adjusting the mirrors when the q-surface moves or the refraction changes. In this case the q-surface is obtained from the real-time EFIT analysis and the refraction from TORBEAM. The accuracy of these calculated values are typically not sufficient to align the ECCD to within ~1-2 cm of the q-surface. The precision has however often proved sufficient to track changes in the positions once correct fine-tuning of the alignment has been found. The working hypothesis is that the alignment error that would result if Active Tracking were used alone consists of a high frequency random error and a systematic error which remains the same or possibly drifts slowly. The high frequency noise is removed by a suitable filter. The systematic error is corrected by a fine-tuning algorithm that uses NTM related signals as additional diagnostics.

There are two methods that are available in the DIII-D control system for automatic fine-tuning of the alignment. They both observe how the NTM responds to adjustments of the alignment and derive a correction in real time.

The first is known as “Search & Suppress.” [7] In this case the alignment is adjusted in steps of typically 1 cm if the mode is not suppressed at a sufficient rate. Each adjustment is held for typically 50 ms to determine if the suppression rate has improved. If the initial step was in the wrong direction the algorithm determines this after a few steps and goes back in the other direction. This method can be very fast if the alignment error is small, in particular if combined with a diagnostic that can give the sign of the error. It may however not necessarily find the best alignment since it only samples a few corrections until a sufficiently good correction is found.

The second fine-tuning algorithm is known as “Target Lock.” [8] In this case the ECCD is swept back and forth at a fairly high speed to see where the ECCD has the maximum effect on the NTM and then returns to that point, thus locking on the target. Fig. 2 shows an example (discharge 149713). At 3.2 seconds into the discharge, the Target Lock algorithm decides that an alignment correction is necessary since the ECCD has been turned on without suppressing the mode. The sweep begins at 3.25 seconds and ends at 3.65 seconds. The controller then returns to the position that was passed 50 ms before the minimum in the mode amplitude (the dip at 3.6 sec). At 3.7 seconds one of the gyrotrons turned off but with the improved alignment the mode is still suppressed despite the lower ECCD.

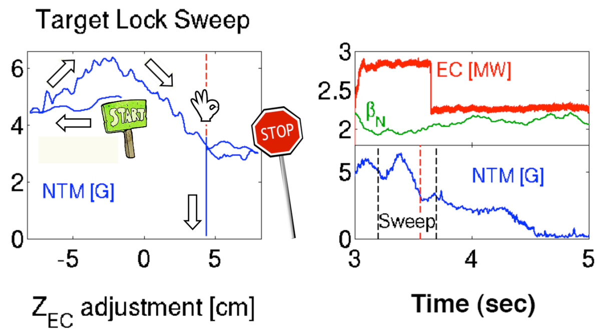

Fig. 2. Alignment correction with the Target Lock algorithm: a) left pane shows mode amplitude plotted versus adjustment of vertical position of the EC. The algorithm begins by moving quickly to -8 cm. The mode begins to rise and keeps rising until the adjustment is almost back at 0. When the adjustment goes to positive values the mode keeps decreasing but after +8 cm it levels off. The algorithm stops at +8 cm and decides that +4.4 cm is optimum since the mode was both small and decreasing there, b) right pane shows time traces of EC power, bN, and the NTM. After adjustment a gyrotron is lost leading to a drop in EC power and bN climbs to 2.15 at 4 seconds which delays the suppression.

Prior to these tests the correct alignment of the ECCD was established by multiple sweeps of ECCD back and forth over a saturated island. The ECCD was then deliberately initially misaligned to check if the Target Lock algorithm would find the right correction. The result was improved alignment in every case.

The experiments reported here were the first to use mirror steering as an actuator for alignment control. For this reason a relatively simple version of the Target Lock algorithm was employed to avoid the risk of sending commands that could not be executed. Plans are under way to refine both the interpretation of the data gathered during a sweep and the logic for the sweep itself. In order to obtain a complete data set for suppression rate versus alignment correction, the Target Lock sweep should extend from one side of the optimum alignment to the other. When the sweep begins, the initial direction will be toward the optimum alignment (if such information about what direction to go is available). During the sweep the Modified Rutherford Equation (MRE) is used to calculate the evolution of the NTM for a range of corrections to both the classical stability parameter Δ' [9] and the alignment. These calculations are compared to the actual NTM evolution and the corrections that make the calculations fit the data are used for predictions. As the sweep progresses and data is gathered at more alignments, the certainty regarding the position of the optimum alignment improves, i.e. the range of possible values (or error bar) decreases. If the initial sweep was in the wrong direction, the alignment will soon come outside the range for where the optimum could possibly be and a decision will be taken to switch and go in the other direction. When the sweep goes through the optimum, the speed must be high enough to get to the other side without completely suppressing the mode and slow enough to have a visible effect on the mode. A suitable speed is selected based on the prediction (which as pointed out becomes more accurate as more data is collected). Once the sweep has gone through the optimum, i.e. is moving outside the range of possible values on the other side, the direction is again switched. At this point the controller may decide to simply apply the inferred correction or continue gathering data with successively smaller sweeps around the optimum. In the event that the NTM goes away before the ECCD has been swept across the optimum, the data gathering must cease and the alignment moves to the best estimate of the optimal position obtained thus far.

There are also two methods under investigation at DIII-D that utilize measurements of electron cyclotron emission (ECE) to fine-tune alignment. ECE measurements can be used to detect the location of an NTM if it is rotating since it then gives rise to temperature fluctuations that have a phase shift between the inside and the outside of the island [10]. One elegant method is to view the ECE from the same major radius and height and along the same polar and azimuthal angles as the gyrotron beams [11-12]. In this case temperature fluctuations originating from inside the deposition will be seen on channels with a higher frequency than the gyrotron frequency and the outside will be viewed at lower frequencies. The goal then becomes to simply move the diagnostic mirror in tandem with the gyrotron mirrors until the phase shift on the diagnostic occurs at the gyrotron frequency. The second ECE method involves pulsing the gyrotron power (typical pulse frequency is 100 Hz) to generate localized heat pulses in the plasma that can be detected by the ECE diagnostic. The mirrors are then steered until the heat pulses appear on the same ECE channel as the phase shift in temperature fluctuations caused by the rotating NTM (a small shift is added to account for the difference between the centers of the heat and current depositions) [13]. This method can potentially inform the Target Lock algorithm what initial direction to take for the sweep and serve as a complement in the analysis.

V. MULTI-MODE SUPPRESSION

Since each of the 6 gyrotrons can be assigned different objectives, it is possible to control several modes, and/or the current profile. However, typically the available gyrotron power isn't sufficient to control more than one mode at a time. Fig. 3 shows the first DIII-D discharge where two NTMs were controlled in the same shot by preemptive suppression that prevented the onset of the NTMs in the first place. Previous discharges showed that without suppression, a 3/2 NTM appears early in the discharge and changes the desired profile evolution. Later in the discharge a 2/1 NTM was controlled.

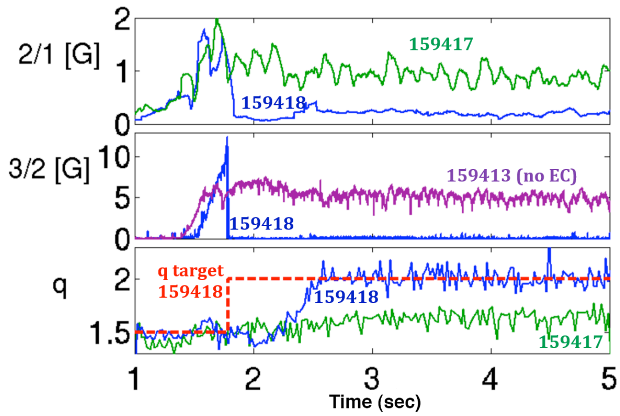

Fig. 3. Multi-mode control with all mirrors aimed at q = 1.5 and switching to q = 2 at 1.8 seconds. All mirrors moved almost exactly together. Top pane shows the 2/1 NTM in blue for shot 159418, also shown is the mode in the previous shot that had EC aimed at q = 3/2 for the entire shot. The middle pane shows the 3/2 mode for shot 159418 and for a shot without EC. The blue trace in the lower pane is the q at the ECCD point for 159418 and 159417. By targeting the 3/2 surface early and then the 2/1 surface, as in 159418, both modes were suppressed.

VI. Catching NTMs

Prior to 2012, NTM control strategies on DIII-D involved driving ECCD continuously on the resonant surface to preemptively suppress the NTM. In some cases fine-tuning of the alignment was made initially by sweeping ECCD back and forth across a saturated NTM. This can be thought of as a manual version of Target Lock and it gave a correction term to Active Tracking that then worked well for all similar discharges. In 2012 studies began of a strategy envisioned for ITER [14] and termed "Catch & Subdue" at DIII-D. In this case the gyrotrons remain off until an NTM is detected. When the NTM is detected the gyrotrons turn on immediately to suppress the NTM. If the detection and alignment (the "Catch") is early enough this technique can promptly suppress the NTM (the "Subdue"). The scenario can minimize the degradation of fusion gain that results from use of auxiliary power, since the EC system can be off when the NTM is not present.

Fig. 4 shows a case of prompt 3/2 suppression with Catch & Subdue. The 3/2 NTM is detected at about 2 seconds. The gyrotrons are turned on and the mode is suppressed within 0.2 seconds. In this shot the ECCD stayed on after suppression since the function to turn off was not yet implemented. A second NTM was triggered at 3.75 seconds and suppressed promptly since the ECCD was already on.

Early detection is crucial for prompt suppression with Catch & Subdue. Fig. 5 compares the evolution of the NTM for 5 similar discharges. In the two cases shown in red the ECCD was turned on when the mode had exceeded a critical amplitude whereas for the three cases in blue the ECCD was turned on with the mode still below this amplitude. Suppression is significantly delayed when the catch is late.

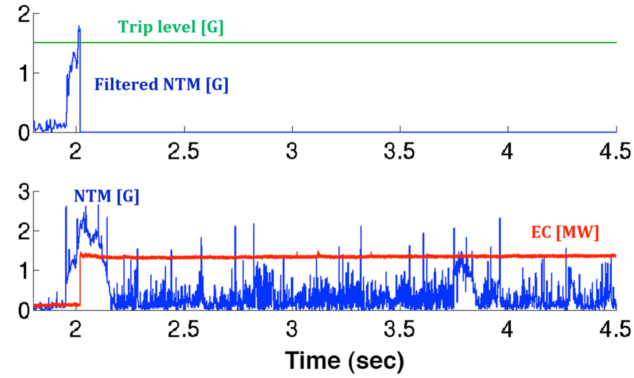

Fig. 4. Prompt suppression of the 3/2 NTM using Catch & Subdue. The real-time calculation of filtered NTM signals turned off after detection in this version of the control system. Normalized beta was controlled to a value of 2. The ratio jECCD/jboot was only 0.5 during the first NTM suppression at 2.2 seconds (partly due to high density) and then drifted up to 0.65 at 3.7 sec when a second (preemptive) NTM suppression occurred.

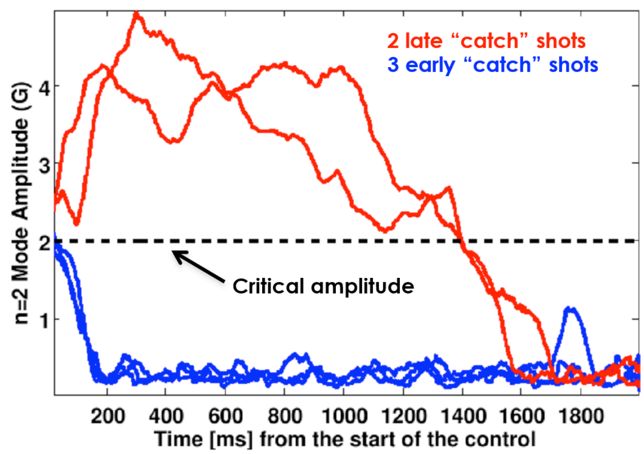

Fig. 5. Showing the 3/2 mode amplitude for 5 cases. The ECCD is turned on at t = 0 in all cases. For the cases shown in red the mode has then already exceed the critical amplitude for prompt suppression which then takes significantly longer.

The minimum power needed for complete NTM suppression is also found to vary depending on when the NTM is intercepted. For these plasmas 1.5 MW of injected EC power was needed to obtain a peak ECCD density (jECCD) equal to the bootstrap current density at the q = 3/2 surface (jboot). For fully saturated 3/2 NTMs (such as the case shown in Fig. 2) more than 2.25 MW of ECCD was needed (corresponding to jECCD/jboot > 1.5), whereas only 0.5 MW sufficed under similar conditions if the ECCD was on continuously for preemptive suppression. The minimum power needed for complete suppression with Catch & Subdue has not yet been tested but complete suppression was seen with powers below 1.5 MW.

Experiments with control of the 2/1 NTM have also been carried out. In this case more power was needed for suppression than for the 3/2. Saturated 2/1 NTMs could not be fully suppressed even with all of the available 3 MW of ECCD. With preemptive suppression 1.5 MW of ECCD was sufficient. Three cases of complete suppression with Catch & Subdue were successful at a power of 2.5 MW but the catches were all done above the critical amplitude since the noise level was too high to set the detection threshold below this amplitude.

VII. Control vision for ITER

The NTM control system for ITER must be part of a larger control function to provide robustly stable control (under normal operating conditions, including expected disturbances) and respond appropriately under fault conditions (known as “exceptions” in ITER parlance). Robustly stable operation begins with real-time control to produce stable profiles (where possible and desirable), including real-time monitoring to predict and prevent the evolution of a potentially unstable profile. The ITER approach to this prediction is to run a faster-than-real-time simulation (FRTS) in the ITER PCS that is capable of predicting the current profile evolution, and also thereby predict the approximate location of rational q-surfaces and enable calculation of onset risk for NTMs. The simulation will also calculate the locations of ECCD. The simulation must be updated in real-time to ensure that the evolution of the simulated plasma, as measured by a comprehensive list of diagnostics, matches the actual evolution. Determining proximity to stability boundaries may make use of active techniques such as MHD spectroscopy, in addition to real-time stability calculations based on projected profile evolution. Island response data from other active perturbations such as Target Lock action may provide further constraints on the FRTS calculation. [15]

The control actions will depend on the present and predicted state of the plasma. During normal NTM-free operation the goal is to minimize the onset risk for NTMs. This may include methods that intentionally excite (stable) NTMs periodically while maintaining active ECCD stabilization [16-17]. In the event that the NTM becomes truly unstable and a seed island is formed, the control system will try to catch the growing mode for prompt suppression. The ECCD is expected to be turned off following full suppression in order maximize fusion gain. The ITER scheme will therefore consist of multiple Catch and Subdue events. Between each such events, alignment will be maintained through active tracking to minimize the time required for suppression upon retriggering of a mode. If at any point the suppression is insufficient and the island nonetheless grows, the control system may decide to turn on more ECCD power or correct a misalignment or go to exception handling. Methods for exception handling are also under active research at DIII-D but are outside the scope of this paper.

VIII. Conclusions

Techniques developed on DIII-D for control of neoclassical tearing modes using ECCD have demonstrated key features of the control strategies envisioned for ITER. It has been shown that the position of the resonant q-surface can be tracked with adequate precision by equilibrium reconstructions that include internal field measurements such as the motional Stark effect. The refraction can be tracked with adequate precision by ray trace analysis. The ECCD is kept aligned to the q-surface using real-time mirror steering. Systematic errors in the alignment can be automatically corrected when necessary. NTMs can be promptly suppressed by turning on ECCD before they exceed the critical mode amplitude. This allows the “Catch & Subdue” strategy to potentially save significantly on the average EC power with a resulting increase of the fusion gain compared to using continuously applied ECCD.

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