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Tearing Mode Suppression as Part of a Comprehensive Real-Time Disruption Avoidance and Mitigation System

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Abstract. Tokamaks designed for burning plasma operation have significant free energy in the poloidal magnetic field and in the thermal stored energy. Protection of the first wall and the vacuum vessel from the effects of a rapid release of this energy (a disruption) is required. While mitigation of a disruption is feasible, avoidance of the disruption is preferable. Suppression of tearing modes that lead to disruption is a key method of avoidance. Electron cyclotron current drive is a demonstrated technique for suppression of tearing modes. The location of the current drive relative to the tearing mode is the critical parameter for successful suppression. Incorporation of this suppression technique in a machine protection system requires continuous aiming of the electron cyclotron waves (for rapid application to island) and a closed-loop optimization of the effect of the current drive on the mode (for maximum effectiveness). Real-time methods to accomplish both of these tasks have been demonstrated successfully in the DIII-D tokamak.

1. Introduction
Optimization of fusion performance in a tokamak requires plasma conditions near various operational limits [1]. The fusion power output increases markedly with increasing pressure, density, and current, but so does the potential for damage to the first wall and the machine structure in the event of a major disruption. In the present ITER design [2], the energy (thermal and magnetic) that can be released in a disruption is ~1 GJ at the design current and pressure. A minimum requirement is to have a machine protection system that can mitigate the effects of energy releases of that magnitude. Ideally, a system would be implemented that avoids such a release altogether in the majority of situations that would otherwise lead to disruptions. The key elements of a system that is capable of suppressing one of the primary instabilities leading to disruption have been demonstrated on the DIII-D tokamak and will be discussed here.

Disruptions can arise from two distinct causes. The first is a systems failure such as failure of a material component or loss of control of the plasma from software or power supply failure. These types of disruptions can be characterized by frequency of occurrence, but are unpredictable. The second class occurs when the plasma conditions exceed a stability boundary. These boundaries can be predicted by theory or characterized empirically, but only with limited accuracy. Both classes of disruption can be preceded by the growth of a tearing instability resonant at the \( q=2 \) surface (\( m=2/n=1 \) tearing mode, where \( m \) is the poloidal mode number and \( n \) is the toroidal mode number). At finite amplitude, the mode locks to the wall and continues to grow, leading to the disruption. For the first class of disruptions, these sequences happen so rapidly that mitigation may be the only remedy. For the second class, the initial tearing mode growth is slow enough that avoidance of the disruption may
be possible by suppressing the mode before it locks. The examples shown here are 2/1 tearing modes that occur as the plasma pressure is increased.

2. Physics Requirements for the Feedback System

Suppression of tearing modes has been successfully demonstrated on several tokamaks by means of localized current driven by electron cyclotron current drive (ECCD) waves [3-5]. This stabilization is found to be most effective when ECCD in the direction of the plasma current is applied [6]. ECCD in the opposite direction is destabilizing, and pure localized heating has only a mild stabilizing effect. In addition to the direction, the suppression is much more effective when the ECCD is localized or, equivalently, when the driven current density is high. Finally, the location of the ECCD relative to the island is very important [7,8]. Measurements during suppression of the 3/2 tearing mode show that the optimum location is current drive centered on the island; offsets on the order of centimeters result in significantly less reduction in the mode amplitude at fixed power [5]. The direction and localization requirements are reflected in design requirements for the optics of the EC wave launcher. The need to locate the ECCD with precision relative to the island requires both a design of a multi-beam launcher capable of precise aiming and the means to determine where to aim the system when needed.

Two types of real-time systems are therefore needed to ensure suppression of the tearing mode as rapidly as possible. Before the mode exists, the aiming of the launchers should track the changes in the position of the $q=2$ surface as the plasma evolves. The goal is to aim approximately in the correct position to suppress the mode in order to minimize the time to suppression. Two calculations are needed — the geometry of the $q=2$ surface and where the ECCD is driven, given the launcher aiming. If a mode occurs, a closed-loop feedback system is needed to optimize the rate of suppression. Prototypes of all these real-time systems are under development on DIII-D.

3. Demonstration of Closed-loop Feedback

Closed-loop feedback to optimize the rate of suppression of 2/1 tearing modes has been demonstrated successfully in DIII-D [8]. Time histories of several relevant quantities are shown in Fig. 1. In all of the plasmas discussed here, a modest $m=3/n=2$ tearing mode is present throughout the high $\beta$ phase of the discharge. This mode is important for maintaining stationary high performance [9], but it does not play any other obvious role either in the onset or in the interaction of the ECCD with the $m=2/n=1$ mode. The mode is initiated intentionally by an increase in pressure up to the $n=1$ no-wall pressure limit (~4 $A_i$) starting at 4.0 s. When the mode amplitude detected by the magnetic fluctuations at the vacuum vessel has exceeded 30 T/s for 50 ms, the control system switches to regulate the normalized pressure at a lower value ($\beta_N = 2.0$). This approximates the loss of pressure due to the existence of a mode in a burning plasma. At 4.5 s, the EC power and the closed-loop feedback system are switched on. The geometry of the $q=2$ surface and the EC optics for a similar plasma are shown in Fig. 2. The ECCD is generated slightly to the low field side of the second harmonic of the electron cyclotron frequency due to the Doppler shift, as shown in Fig. 2. The feedback system in this case changes the value of the magnetic field $B$ to maximize the rate at which the magnetic perturbation from the tearing mode is reduced. Feedback using variation of the major radius of the plasma at fixed $B$ to optimize the reduction of the mode amplitude has also been demonstrated. In ITER, change of the launcher aiming is the most attractive method to optimize the suppression. This capability does not yet exist on DIII-D. The algorithm used for the feedback control takes a pre-determined initial perturbation in $B$, then a decision is made concerning further steps in $B$ based on the plasma response. The algorithm’s actions for two cases — one where the initial step is away from the direction of the optimal aiming, and one where the initial step is in the direction of the optimal aiming — are shown in Figs. 3 and 4, respectively. There is a significantly shorter time to achieve suppression for the case where the initial step is in the direction of the optimal location, but the mode is suppressed eventually in both cases. In the case of the initial step away from the optimum (Fig. 3), the mode is suppressed while misalignment of 1–2 cm is calculated. This probably indicates the available power is more than adequate to suppress the mode, although uncertainty in the location of the $q = 2$ surface from the reconstruction cannot be ruled out. Determining the direction of the feedback by real-time calculations of the $q=2$ surface geometry and the EC beam optics may allow the faster suppression. This has not yet been attempted. Alternatively, a better searching algorithm could be developed. The feedback
system makes changes in $B$ equivalent to steps of $<1$ cm in relative position of the ECCD deposition location and the tearing mode, as shown in Figs. 3 and 4. The fact that changes in the reduction rate of the mode amplitude can be observed with changes in relative location of this magnitude emphasizes the sensitivity of the suppression to the relative location of the ECCD and the tearing mode.

![Fig. 1](image1.png)

**Fig. 1.** Time histories of plasma quantities in the case of closed-loop optimization of the suppression of an $m=2/n=1$ tearing mode. (a) (cyan) Plasma current (x10) (MA), (grey) neutral beam injection (NBI) power (MW), (black) time-averaged NBI power (MW), (red) EC power (MW), (b) amplitude of $n=1$ magnetic fluctuations at the vacuum vessel (G), (c) (red) $\beta\nu$, (green) $4\ell_i$ (estimate of the no-wall ideal $n=1$ pressure limit, (d) $B$ (T).

**Fig. 2** Cross-section of the DIII-D vacuum vessel and a typical plasma shape for the experiments described here. The optics of the EC waves are modelled by ray tracing. The central ray is shown in magenta, while the size of the beam is shown in cyan. The nearly vertical green lines labelled 2 and 3 show the positions of the second and third harmonics of the electron cyclotron resonances, respectively. The dashed lines are poloidal flux contours at increments of 0.1 in $\rho$, the square root of the normalized toroidal flux. The colored contours show the location and breadth of the ECCD, with red indicating the maximum current density.

**4. Demonstration of Real-time Tracking**

Real-time tracking of the $q=2$ surface has also been demonstrated successfully in DIII-D. The geometry of the $q=2$ surface is calculated in real-time using a reduced version of the EFIT free-boundary Grad-Shafranov equation solver in the digital control system. The solver uses both external magnetics and internal measurements of the field from motional Stark effect (MSE) spectroscopy to calculate the $q=2$ surface geometry. The geometry of the EC beam is parameterized for the case under study. A real-time calculation of EC beam including refraction is under development. The case shown in Fig. 4 demonstrates the tracking of the $q=2$ surface after the tearing mode is suppressed at 4.8 s. At constant pressure, the current profile in the absence of the mode evolves such that the $q=2$ surface
Fig. 3 Case with initial feedback step away from the optimum location. a) Major radius (m) of the ECCD deposition (red) and the $q=2$ surface (black) at the height of the maximum driven current density vs. time (ms), b) $\rho$ value of the ECCD deposition (red) and $q=2$ surface (black) vs. time (ms), c) Amplitude of the n=1 magnetic fluctuations at the vacuum vessel (G) vs. time (ms), d) Amplitude of the n=1 magnetic fluctuations at the vacuum vessel (G) vs. $B$ (T) for times between 4500 ms and 6500 ms. Comparison of (c) and (d) gives the timing of the changes in $|B|$.

Fig. 4. Case with initial feedback step toward the optimum location. (a) Major radius (m) of the ECCD deposition (red) and the $q=2$ surface (black) at the height of the maximum driven current density vs. time (ms), (b) $\rho$ value of the ECCD deposition (red) and $q=2$ surface (black) vs. time (ms), (c) Amplitude of the n=1 magnetic fluctuations at the vacuum vessel (G) vs. time (ms), (d) Amplitude of the n=1 magnetic fluctuations at the vacuum vessel (G) vs. $B$ (T) for times between 4500 ms and 6500 ms.

moves to larger minor radius. At the location of the ECCD, this corresponds to smaller major radius, as shown in Fig. 4. The feedback system reduces $B$ in order to maintain the relative location of the ECCD and the $q=2$ surface. A further test of the real-time tracking is shown in Fig. 5. In this case, the normalized pressure is increased following suppression of the tearing mode. The $q=2$ surface varies both due to the shift of the surfaces with increasing pressure and change in the current profile due to
the increase in bootstrap current. In this case, the pressure is then increased to a level exceeding the original level at which the mode was destabilized. Once the mode amplitude is reduced below a preset threshold, the closed-loop feedback is stopped and the relative position of $q=2$ and the ECCD are maintained fixed by varying $B$ (Fig. 5). The full power duration of the EC power is limited to 2 s. Shortly after the end of the EC pulse, the 2/1 tearing mode re-appears (Fig. 5), indicating the ECCD is essential to maintaining this high pressure level without instability.

5. Summary

Two key real-time systems for tearing mode suppression and stabilization have been demonstrated on DIII-D — closed-loop optimization of suppression of the $m=2/n=1$ tearing mode and real-time tracking of the $q=2$ surface. A closed-loop feedback system adjusts the relative location of the ECCD and an existing tearing mode to optimize the rate of suppression. The interaction of the ECCD and the mode is quite sensitive to the relative location. The real-time tracking of the $q=2$ surface is shown to account for changes in the $q=2$ surface with increased pressure and changing current profile. This will be essential in ITER to position the EC beam to control the mode at the earliest possible time following detection. Deployment of a complete suppression system should be considered an essential element of the disruption control system, since effects of both a disruption and the mitigation system may have a significant impact on operations in a tokamak the size of ITER.

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