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Closed Loop Feedback of MHD Instabilities on DIII-D

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The external kink can limit the achievable beta, hence performance in many magnetically confined plasma fusion devices including tokamaks [1], reverse field pinches, and spherical tori. The addition of a close fitting perfectly conducting wall can stabilize the mode but, with finite conductivity walls, the growth rate of the mode is only slowed to of order the wall time constant. Methods proposed to extend beta limits closer to the ideal wall limit in future reactor concepts include maintaining the mode rotation, or active feedback to compensate for flux leakage using coils external to the wall [2,3]. In this paper we will discuss confirmation of the initial results of the Resistive Wall Mode (RWM) feedback stabilization experiment reported at the 26th EPS conference [4] by using a rapid I_p ramp to reproducibly excite the RWM. In addition, we will present the details of feedback-stabilized RWM characteristics observed during the rapid I_p ramp.

THE FEEDBACK SYSTEM

The present feedback system on DIII-D is based on an existing “belt” of six midplane picture frame coils (the “C-coils”), each spanning 60º in toroidal angle. A set of six saddle loops installed just outside the vacuum vessel sense the flux leakage and three switching power amplifiers (SPAs) drive the C-coils to compensate for “lost flux”. The frequency response of the system is limited by the maximum voltage available to the SPAs of ≈ 250 V and the inductance and resistance of the C-coils. At the maximum feedback current of 5 kA, the maximum frequency is 40 Hz. Experiments last summer showed that the n = 1 flux leakage from the vacuum vessel could be compensated by the feedback system and the amplitude of the MHD mode could be reduced [4]. Code simulations predict that the present feedback system could increase the Resistive Wall Mode beta limit by 10%–15% [5].

THE RESISTIVE WALL MODE INDUCED BY A RAPID I_P RAMP

In the experiments described here, the RWM beta limit was reduced by ramping the plasma current at rates up to 1.5 MA/s, creating a skin current on the plasma edge. Some representative waveforms from one such plasma shot are shown in Fig. 1. The beta was increased prior to the ramp in plasma current by stepping up the beam power to ≈ 9 MW. In this example the plasma transitions to H-mode at ≈1.1 s as evidenced by the increase in edge rotation during the ELM-free period, and by the drop in H-α light. Concurrent with the onset of ELMs, the edge rotation begins to slowly decrease. While the drop in rotation could be due to several things, including error field amplification due to the high beta or secular changes in the equilibrium plasma parameters, it is instructive to note that each ELM event is accompanied by a sharp drop in rotation. Under these conditions, the plasmas reproducibly suffered minor disruptions between 1.35 s and 1.4 s; the timing of RWM mode onset is possibly related to the drop in edge rotation rate below some threshold level.

The disruption typically has three phases. It begins with a slow collapse of the edge electron temperature in Phase I, indicated in Fig. 2. In Phase II, as the thermal collapse progresses and the plasma rotation slows, a threshold is reached where the mode grows rapidly. Concurrent with the rapid growth of the mode, the thermal collapse accelerates. In Phase III, the final phase, there is a magnetic reconnection and a disruptive thermal quench.

In Figure 2 it can be seen that the degradation in confinement preceding the disruption begins at 1.365 s with the collapse of the edge electron temperature. At the onset of the slow thermal collapse, the resistive wall mode amplitude is <1 Gauss, at the threshold of detectability. Soft x-ray arrays at toroidal angles of 45° and 195° show that most of the displacement of the electron temperature contours in Phase I and II is axi-symmetric, thus an axi-symmetric thermal collapse rather than displacement from a mode. Possible explanations for the thermal collapse include an influx of impurities caused by the small amplitude RWM, or the formation of magnetic islands coupled to the RWM. This result suggests that the RWM is just one part of the physics involved in the disruption.

CLOSED LOOP FEEDBACK RESULTS

In Fig. 3 is shown data from a shot in which the onset of the resistive wall mode was delayed by 100 ms, similar to what had been previously achieved under different conditions [6]. The feedback logic used was "mode control" where the sensor signal is compensated by the feedback coil current so as to leave only a signal from the mode. In the β_N frame, a trace from the discharge of Fig. 1 without feedback is included for comparison. As can be seen in Fig. 3, the H-mode onset and slowing of edge rotation follow a very similar pattern to what was observed in the plasma shown in Fig. 1. The feedback is turned on at 1.35 s at which time the edge rotation stabilizes and the ELM activity is much reduced (as measured by the amplitude of the H-α bursts). The

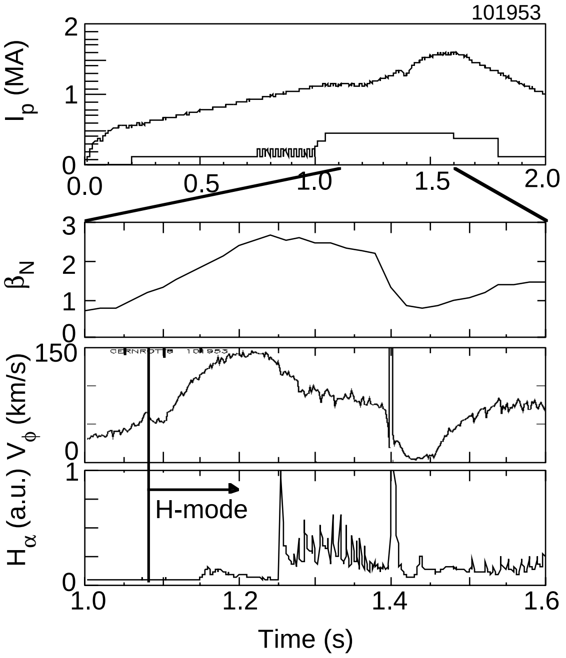

Figure 1. Traces showing the evolution of the plasma current and neutral beam power, β_N, rotation rate at r/a ≈ 0.8 and H-α light as monitored with a photo-diode.

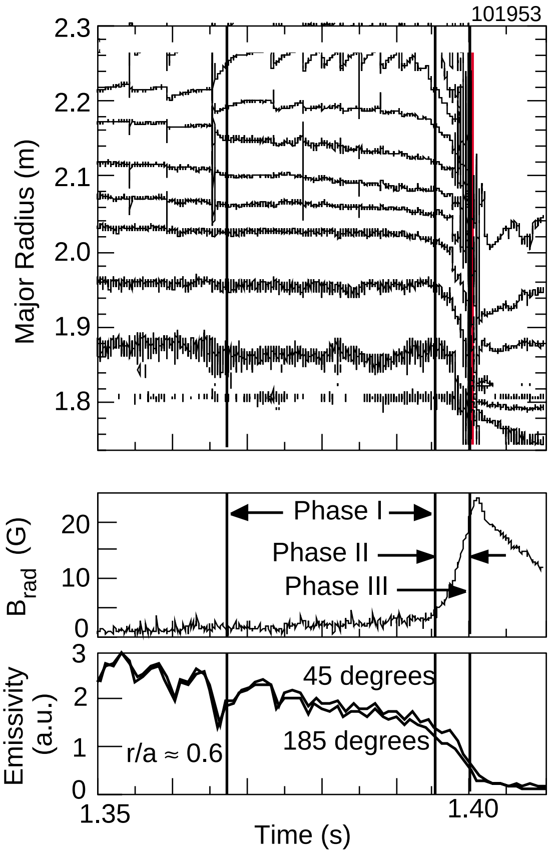

Figure 2. T_e contour plot of the disruption shown in Fig. 1. The lower traces show the amplitude of the RWM and x-ray emissivity from two toroidally separated arrays.

reduced ELM amplitude could be consistent with an increase in radiated power from the edge plasma, associated with an impurity influx as the RWM is stabilized at a small but non-zero amplitude.

In Fig. 4, the feedback stabilization period is shown in more detail. The radial field amplitude of the RWM inferred from the saddle loop data is ≈3 G. There is some uncertainty in this estimate due to the uncertainty in compensating for the n=1 component of the intrinsic error fields. The inferred phase of the mode is such as to predict an inward displacement at the location of the ECE radiometer. The amplitude of the RWM remains constant at approximately 3 G until ≈1.48 s. At this time, the RWM begins to grow and within 10 ms exceeds an amplitude of about 15 G. A complete thermal quench of the plasma follows (neutrons, ion and electron temperature).

The final growth of the resistive wall mode leading to the thermal quench is likely triggered by the RWM mode drive becoming stronger as the pressure and current density profiles evolve. As shown in Fig. 5, the final growth rate increases from ≈300 s^{-1} (~$1/\tau_w$) without feedback to ≈800 s^{-1} in the most strongly stabilized cases, consistent with an MHD instability drive that increases with time. (The variation in onset time in the figure results from variation of the feedback control algorithm and gain values.) The feedback system tracks the phase and amplitude of the mode up to the thermal quench with a lag of about 0.3 ms. There is no apparent saturation of the feedback amplifiers. This indicates that the present feedback gain is not strong enough to accommodate the rapidly increasing ideal MHD growth rate.

In other experiments in this campaign, it was found that with lower I_p ramp rates the onset of the RWM could be delayed for longer periods and the efficacy of derivative, proportional

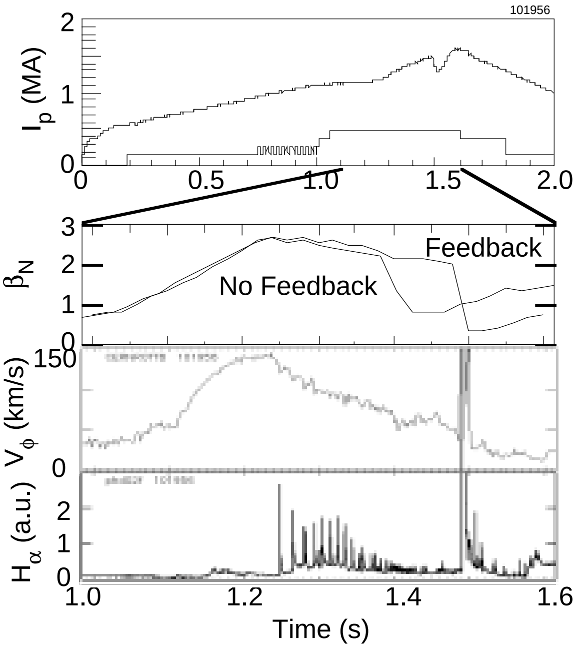

Figure 3. Traces showing the evolution of the plasma current and neutral beam power, β_N (with and without feedback), rotation rate at r/a≈0.8 and H-α light.

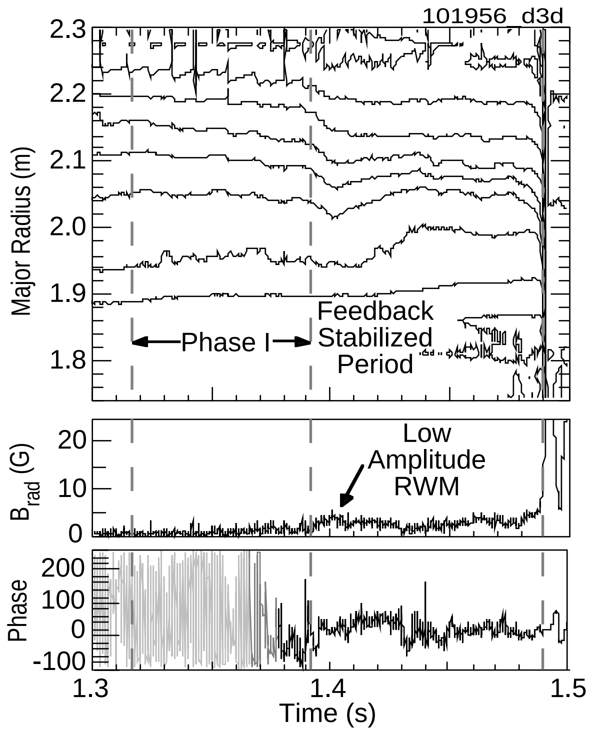

Figure 4. T_e contour plot of the disruption shown in Fig. 3. The lower traces show the amplitude and phase of the RWM.

and integral gain terms were investigated. An additional 12 sensor loops above and below the midplane have been installed to measure the poloidal structure of the mode and to provide the sensor coils to support the planned extension of the feedback coil array.

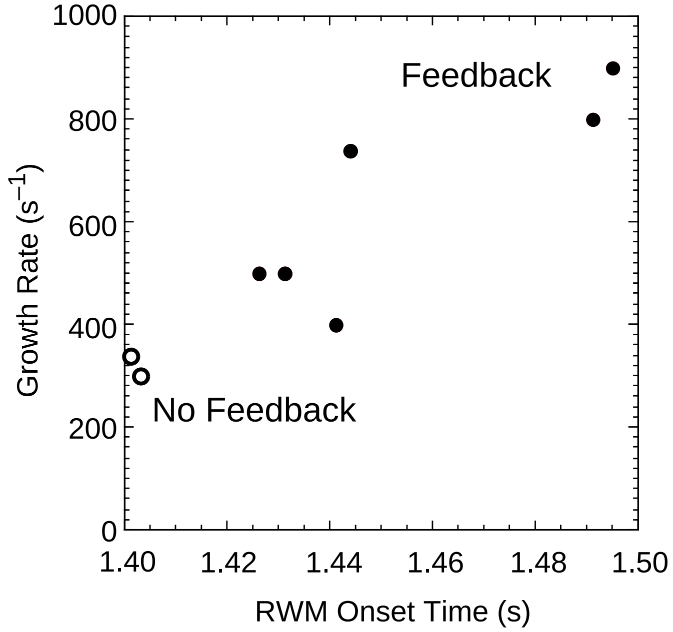

Figure 5. Observed growth rate vs. onset time of the RWM.

Future plans include improvements in the sensor coils and possible extensions to the feedback coil system (additional coils above and below the midplane and SPAs to drive them). Simulations suggest that reducing the height of the sensor coils will improve the system. Likewise, sensors inside the vacuum vessel, possibly measuring poloidal rather than the radial field can also improve performance.

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