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The Resistive Wall Mode Feedback Stabilization Experiment on DIII-D

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Abstract

The feedback stabilization of the Resistive Wall Mode (RWM) has begun in the DIII–D Tokamak. The main objective of the experiment is to stabilize the RWM by effecting a ‘‘perfectly’’ conducting shell through active compensation of the n = 1 flux leaking through the resistive vacuum vessel. The preliminary results indicate that the n = 1 flux leakage from the vacuum vessel can indeed be compensated by the feedback system, and the amplitude of the magnetohydrodynamic mode can be reduced and the discharge's duration prolonged with a judicious choice of feedback parameters. We briefly describe the initial experimental results and also summarize a new feedback simulation code in toroidal geometry, which should prove useful for better understanding of the RWM feedback process.

1. Introduction

Previous DIII–D experiments have indicated that near the high beta limit, the stability of the ideal MHD global kink mode is strongly influenced by the vacuum vessel [1,2]. Since the vacuum vessel has finite conductivity, the magnetohydrodynamic (MHD) mode is manifested as the RWM, where the mode growth rate is reduced to a low value, of the order of the inverse of the L/R time of the vacuum vessel. Accordingly, the required power and bandwidth for the RWM feedback system can be reduced to a modest value. A preliminary open-loop control experiment showed promising results in temporarily postponing the RWM onset [1].

The schematic diagram of the feedback system in DIII–D is shown in Fig. 1. The present feedback coil set (C-coils) consist of six window frame coils located outside the vessel on the midplane. They are energized by three newly installed switching-power-amplifiers with a frequency range of 0–100 Hz, which can produce an n = 1 radial magnetic field pattern of up to 14 G on the vessel surface. For the present preliminary experiment, however, 1/2–2/3 of the current capacity was pre-programmed for field error correction thus limiting the available feedback field to about 5 G at the plasma surface. New saddle coil sensors monitoring then = 1 helical flux leakage were mounted outside of the vacuum vessel wall.

The RWM feedback control algorithms are implemented by the DIII–D digital Plasma Control System (PCS). Prior to the PCS feedback logic process, the six sensor signals are combined to give three signals to observe only n = odd components. In the PCS, the three sensor signals are decomposed into sine and cosine toroidal components to minimize the propagation of noise to the logic output. The feedback logic schemes implemented in the PCS are: the ‘‘Smart Shell’’ [3], where the feedback system prevents the leakage of n = 1 flux through the vacuum vessel wall, making the wall appear to be ideal, the ‘‘Fake Rotating Shell,’’ where the feedback system makes the wall appear to be rotating with respect to the MHD mode, and [4] a Proportional-Derivative (PD) feedback scheme, where a response term opposing mode growth is included. The PCS can respond within 200 μs, including DA conversion, which is considerably less than the power supply switching period of 330 μs. The PD scheme was used in the experiment.

2. Initial Experimental Results

These first experiments show clearly that the feedback control has a stabilizing effect on the RWM, as anticipated. Feedback was applied in a negative central shear plasma with normalized beta ($\beta_n = \beta(\%)/(I_p(MA)/a(m)B_t(T))$ near the ideal no-wall stability limit approximated by $\beta_n \approx 4l_i$ (Fig. 2). By correlating the behavior of the feedback current with bulk plasma parameters such as the plasma rotation at the q = 2 or 3 surfaces it is possible to observe some dynamics of the feedback process. Fig. 3 shows (a) the relation of β_n and li, (b) the plasma fluid rotation, (c) feedback sensor signals at three locations, and (d) three feedback coil currents with [Fig. 3(A)] and without [Fig. 3(B)] feedback. When β_n reaches near to the limit at t = 1400 ms, an MHD mode is gradually excited accompanied by the reduction of the plasma rotation. Without feedback (constant coil current), the mode grows rapidly at t = 1440 ms and a sudden drop in beta was observed. When the feedback is applied and the plasma rotation approaches zero, the feedback system responds to the flux change, clearly visible at t = 1490 ms, 1530 ms, and 1620 ms. The phase shift between the three power supply currents, also indicates that the mode is identified by the PCS as an n = 1 perturbation and the power supply responds accordingly. At 1620 ms, even with the plasma rotation nearly zero, the feedback system managed to avoid the occurrence of a major disruption by supplying larger current.

The major disruption which took place at t = 1720 ms was somewhat unusual, since the plasma rotation was not reduced which is a typical indication that the mode precursor is building up. One possible cause is a control instability. A small amplitude n = 1 mode was observed to suddenly change its toroidal phase by 180 degrees, so that it is reinforced rather than opposed by the applied n = 1 field; rapid growth follows this phase change. Another issue was the gain limitation for the present experiment, since the 1/2–2/3 of the power supply current was used for the error field correction as a pre-programmed fixed current.

These results indicates that there is a possibility that a discharge can be extended with the feedback system. Although the actual extension for this shot was modest, of the order of 100 ms, this is about extra 15 wall-times, and the system seems to have survived a few mode onsets before the major disruption took place. Further improvements in the duration should be possible with optimization of the feedback control and theoretical modeling.

3. A Feedback Simulation Code with Resistive Shell in Toroidal Geometry

A new toroidal model for feedback simulations has been developed to extend earlier work [3–6] that conceptualized the feedback logic in the cylindrical limit. Although the analyses of RWM feedback in this limit have allowed the development of various feedback schemes, the cylindrical model has serious shortcomings in that it does not include poloidal coupling and the toroidicity effect on the mutual inductances. The VACUUM code [7] is currently being modified to include these effects.

The modification consists of three parts: (1) plasma-vacuum interface, (2) the 3D eddy current on the 2D approximation of resistive vacuum vessel, and (3) the active coil system represented by a suitable set of toroidal and poloidal harmonics. A PEST or GATO surface eigenmode of an ideal kink is assumed, whose structure remains unchanged during the feedback process, allowing only the magnitude to change. (This is a helical rigid displacement approximation similar to that of the rigid displacement assumption in the n = 0 vertical feedback stability schemes.) The couplings between the plasma perturbation and the inside surface of the resistive vacuum vessel, and also between the outside surface of the vessel to the feedback coils were calculated using the Green's theorem technique of Ref. 6.

The treatment of the resistive vacuum vessel is formulated in axisymmetric toroidal geometry using the thin shell approximation, and the associated continuity of the normal magnetic field which relates to the shell's electric field and current through Faraday's law; Ampère's law gives a relation for the jump in the tangential component through the vessel wall. This results in an operator made up of a set of coupled time dependent equations relating the shell response to the plasma and feedback coil. The eddy current pattern for each eigenmode of this operator is found. The lowest eigenvalue is 6 ms without plasma, which closely agrees with the estimate given by the finite-element SPARK code [8]. This eigenvalue is reduced to 3.5 ms when a plasma is present in the chamber.

The response of the resistive vacuum vessel is calculated due to the ideal plasma perturbation but without the feedback coil. In the limit of slow variation in time, we noticed that the eddy current pattern due to this driving source which is localized only on the outboard side of the vacuum vessel can be represented with as few as four wall eigenmodes thus promising that a not too complex set of feedback equations may be sufficient. Further analyses may be used to assess the tolerance to the non-uniformity of the vacuum vessel and also to design the active coil geometry, which can only partially cover the vessel.

4. Summary

It was demonstrated that the feedback system has coupled to the MHD modes by compensating the eddy current on the resistive vacuum vessel. The plasma duration has been extended by stabilization of the MHD events. The refinement of the feedback system will require further theoretical understanding, which will be provided by a new toroidal simulation code.

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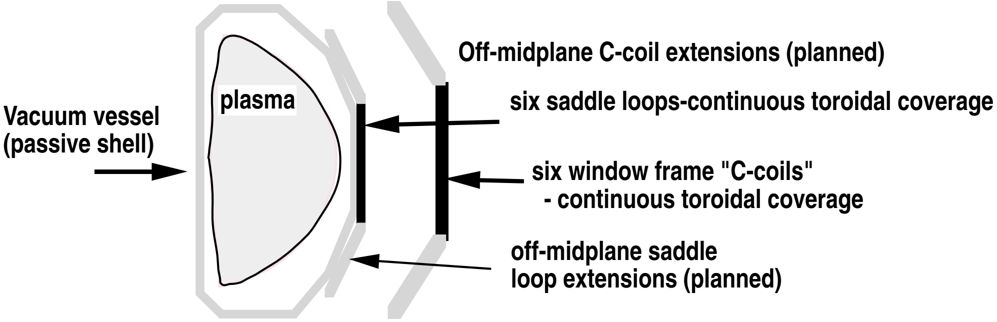

Fig. 1. The schematic diagram of DIII–D RWM feedback system.

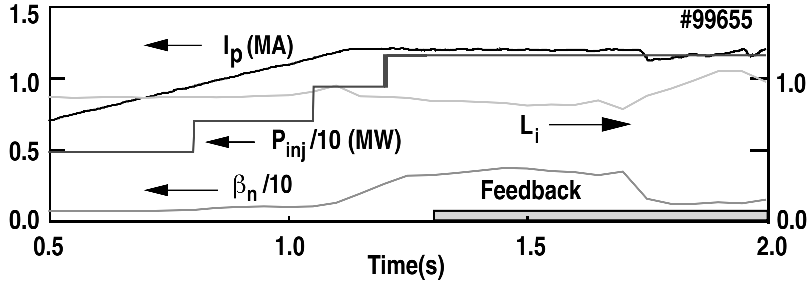

Fig. 2. The mode feedback stabilization was applied after the discharge reached steady-state.

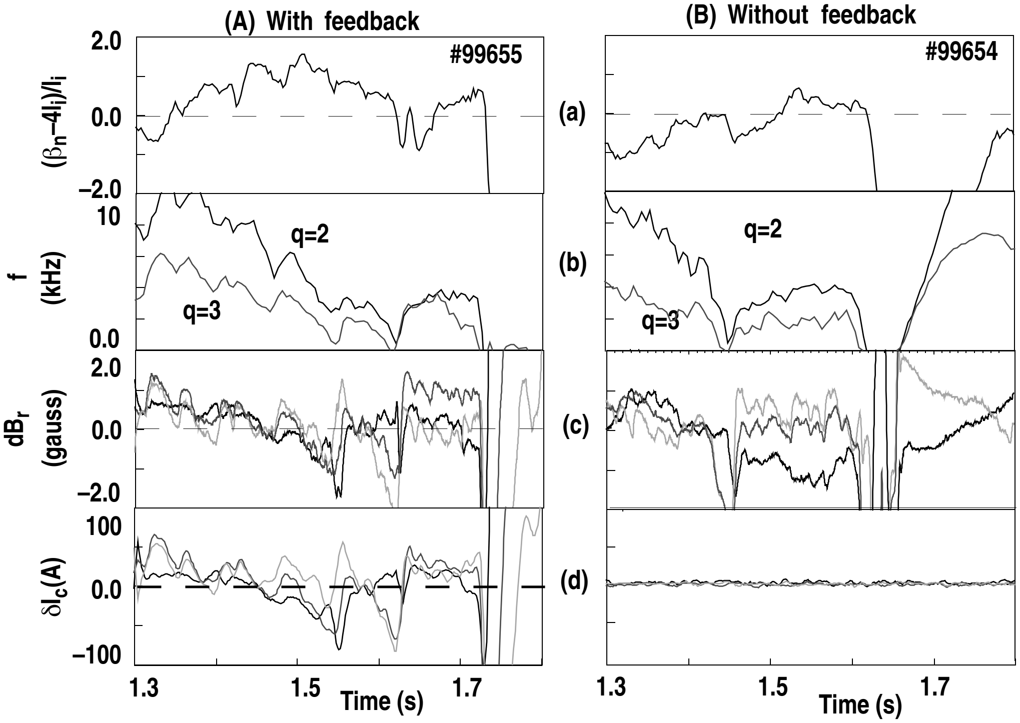

Fig. 3. Comparison between discharges (A) with feedback applied (#99655) and (B) without feedback (#99654). (a) $(\beta_n - 4l_i)/l_i$, (b) the plasma rotation at q = 2, three surfaces, (c) the n = 1 component of flux measured by the three saddle loop pairs, and (d) the three feedback control currents.