Resistive Wall Mode Dynamics and Active Feedback Control in DIII–D* EX

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Recent DIII–D experiments have shown that the n=1 resistive wall mode (RWM) can be controlled by an external magnetic field applied in closed loop feedback using the six element error field correction coil (C-coil). The RWM constitutes the crucial limitation to normalized beta and the duration of the high normalized performance phase in recent DIII–D advanced tokamak plasma experiments [1]. The toroidal rotation achieved in DIII–D plasmas does not seem sufficient to completely suppress the RWM, suggesting that feedback control is needed.

The realization of a compact and economical fusion reactor based on any of the leading magnetic confinement concepts requires stabilization of the low toroidal mode number *n* ideal magnetohydrodynamic (MHD) kink mode. A perfectly conducting wall placed close enough to the plasma can provide this required stabilization. However, in the presence of a real wall, the kink mode can persist as the resistive wall mode, where the mode rotation and growth rate (f and γ respectively) are limited according to: $f \le 1/2\pi\tau_w$ and $\gamma \le 1/\tau_w$, with τ_w the wall resistive decay time. We will discuss here two distinct approaches to stabilization of this mode: plasma rotation and active feedback using magnetic coils.

While several theories have predicted that the presence of dissipation and rotation in the plasma can stabilize the RWM, the toroidal rotation achieved in DIII–D plasmas does not seem sufficient to completely suppress the instability. Previous DIII–D experiments [4] have demonstrated that the plasma rotation always slows when $\beta_N > \beta_N^{\text{no wall}}$. Here $\beta_N = \beta/(I/aB)$, $\beta = 2\mu_0\langle p\rangle / B_0^2$, $\langle p\rangle$ is the volume averaged pressure, B_0 is the external toroidal field, I is the total toroidal current in MA, a is the plasma minor radius, and $\beta_N^{\text{no wall}}$ is the β_N limit predicted without wall stabilization). With improved measurements, we have recently found that small amplitude, slowly growing (often $\gamma \ll 1/\tau_w$) modes can usually be observed whenever $\beta_N > \beta_N^{\text{no wall}}$. The plasma rotation that previously was measured as threshold for stabilization of the RWM might actually mark a transition from a very slowly growing RWM (growth rate $\ll 1/\tau_w$) to a "fast" RWM growing at rate $\sim 1/\tau_w$. Such behavior is in qualitative agreement with the predictions of a non-linear RWM model [5] where the plasma rotation is determined self-consistently from torque balance.

Active control is needed to achieve and sustain $\beta_N > \beta_N^{\text{no wall}}$, since the slowly growing, often bursting, RWMs limit the steady-state value of β_N to approximately the limit calculated in absence of a conducting wall. The DIII–D experiments on feedback stabilization of the RWM use the six element error field correction coil located at the mid-plane, outside the DIII–D vessel. An array of 6 sensor saddle loops, located outside the vessel, monitors the penetration of the n=1 helical flux through the resistive wall. These experiments represent the first application of magnetic feedback on non-axisymmetric modes in a large tokamak. The results are examined in comparison to the predictions of several models of the feedback system. These include the electromagnetics code VALEN, which accurately models the 3-dimensional geometry of the resistive wall and the coil-sensor pairs, and a 1-dimensional simplified analytical model that includes the effects of non-ideal feedback circuit components [3].

Initial active feedback experiments have shown a clear effect of the feedback system on the evolution of the RWM. We recently carried out an evaluation survey of several feedback schemes, using a target plasma with reproducible RWM onset and characteristics. Without feedback, these plasmas survive above the no wall beta limit until the plasma rotation decreases below a threshold value, at which point a disruption is caused by a RWM growing

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with $\gamma \sim 1/\tau_W$. In discharges with feedback, the RWM appears when the same rotation threshold is crossed, but the externally applied n=1 magnetic field is able to hold the mode to a very small amplitude, prolonging the plasma duration above the no wall limit. Control is eventually lost when the RWM growth rate becomes exceedingly large, presumably due to the continuous rotation slowing (see Fig. 1). The observations are consistent with a small increase in the beta limit obtained with feedback control of the RWM using the present un-optimized coil set, as predicted by both the VALEN code and the 1-dimensional analytical model.

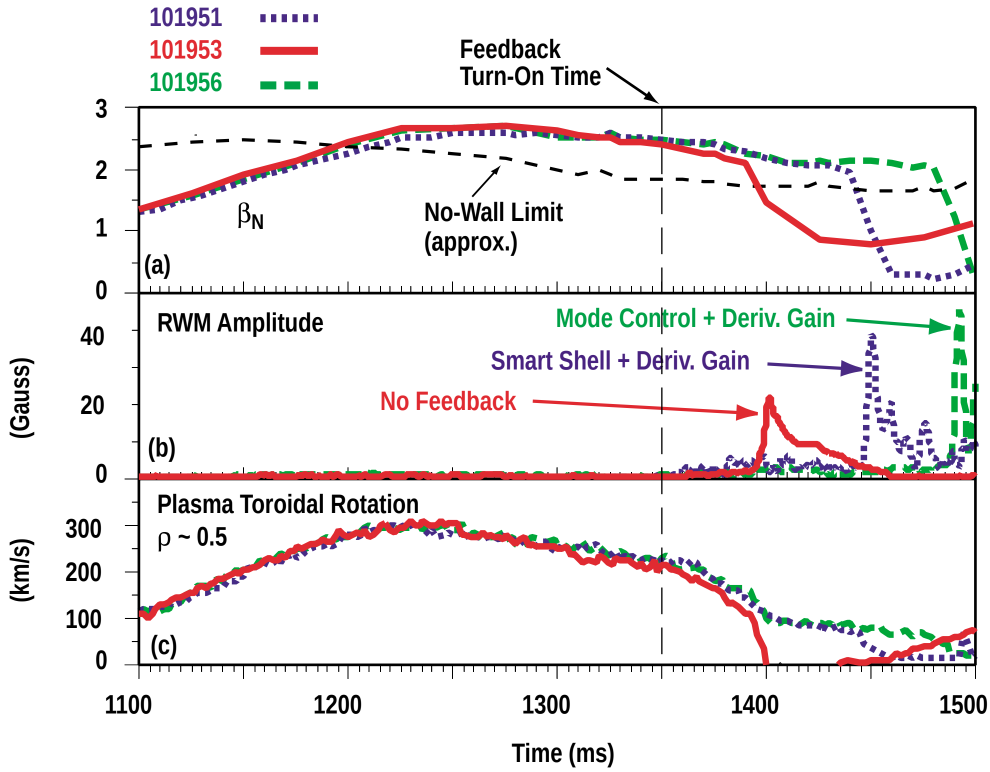

Fig. 1. Comparison between discharges with feedback applied (#101951, dotted lines, and #101956, dashed lines) and without feedback (#101953, solid lines). The "smart shell" feedback responds to the total (mode plus external) radial field measured by the sensor loops, while in the "mode control" logic the external field is subtracted from the sensor signals. Shown are traces of (a) β_N and an approximation of the no wall limit based on the internal inductance, (b) n=1 amplitude of the RWM at the sensor loops, and (c) plasma toroidal rotation at normalized minor radius $\rho \sim 0.5$.

Future experiments will make use of 12 new saddle loop sensors above and 12 below the existing mid-plane array, and will focus on quantification of the beta limit improvement achieved with optimized feedback parameters in different feedback algorithms. The results will be used to benchmark the numerical models of the feedback stabilization process. These codes can then be used as guidance in the design of an upgraded RWM feedback system that will be able to demonstrate sustained operation at β_N significantly exceeding $\beta_N^{\text{no wall}}$.

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