Active Control of Resistive Wall Modes in High Beta, Low Rotation DIII-D Plasmas* EX-S

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Active control of the n=1 resistive wall mode (RWM) with rotation below the critical value for stabilization has opened access to new regimes of high performance in recent DIII-D tokamak experiments. Very high plasma pressure combined with high bootstrap fraction and high energy confinement are sustained for almost 2 s, or ten energy confinement times [1]. The experimental limit to the pressure is observed to agree well with the ideal MHD, ideal-wall stability limit for low-n kink modes. Stability calculations for n = 1,2,3 show that the ideal-wall limits increase with q_{min} increasing above 2. These scalings, which are consistent with the experimental results, indicate the possibility to operate at plasma β of about 6% with wall stabilization, suggesting a possible path to high fusion performance, steady-state tokamak scenarios. Here $\beta = 2\mu_0 \langle p \rangle / B_0^2$ is the ratio of volume-averaged plasma pressure to toroidal magnetic field pressure.

Previous DIII-D experiments [2] have demonstrated sustained stabilization of the $n = 1$ RWM by plasma rotation at β approaching the ideal-wall limit, through improved correction of the resonant error field using an external coil set. However, the rotation threshold for RWM stabilization is higher at $q_{min} > 2$, as shown in Fig. 1 by measurements of the threshold obtained with rotation braking experiments at different values of q_{min}. Thus, the plasma rotation obtained with optimal error field correction is only marginal for RWM stabilization in these high beta discharges with $q_{min} > 2$. (This may be the same RWM regime as in the ITER steady-state scenario, for which the predicted values of the plasma rotation and of the rotation threshold for RWM stabilization are very close to each other [3].)

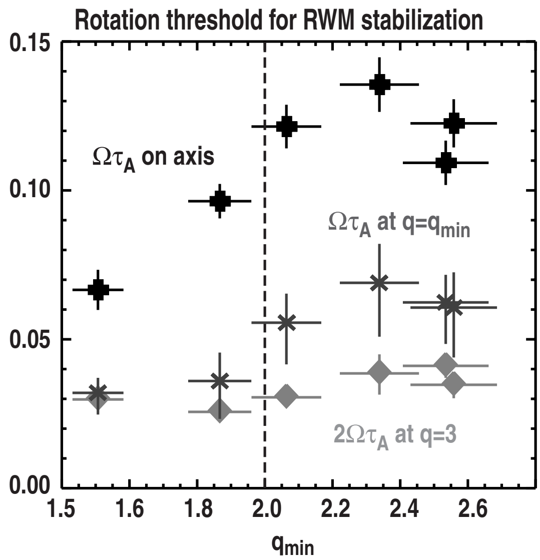

Fig. 1. Rotation threshold for RWM stabilization measured in discharges with different values of q_{min}.

Active feedback control of the RWM is required to robustly achieve high beta at $q_{min} > 2$. Hence, an essential tool for the sustainment of these discharges is the simultaneous feedback control of the error field and the RWM, using the two sets of non-

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axisymmetric coils in DIII-D. The external coils (C-coils) are used to maintain optimal error field correction so as to maintain high levels of plasma rotation for rotational stabilization of the RWM [2]. The internal coils (I-coils) are powered by high bandwidth audio amplifiers and provide direct resistive wall mode stabilization during transient periods of low rotation, e.g. following a large edge localized mode (ELM). Having two independent coil sets affords us the capability to optimize each feedback system for its task: high gain, slow response for dynamic error field correction; low gain, fast response for direct stabilization of the RWM. Figure 2 shows the comparison of two high-β_N, high-$q_{\min}$ discharges using active RWM feedback, with one discharge where the I-coil feedback currents were frozen during 10 ms notches. [Here $\beta_N = \beta/(I/aB_0)$, with I the total toroidal current, B_0 the toroidal magnetic field, and a the plasma minor radius]. Rotational stabilization works during the first two notches, but an RWM grows and disrupts the plasma during the third notch, following a large ELM. We propose that in absence of active feedback, the transient rotation drop following the ELMs is responsible for RWM onset which leads to further rotation damping and to unstable RWM growth. Large ELMs observed during the active feedback periods do not lead to RWM onset. The comparison discharge with continuous feedback also remains stable throughout the high-β_N ELMing phase, showing the efficacy of the RWM feedback system.

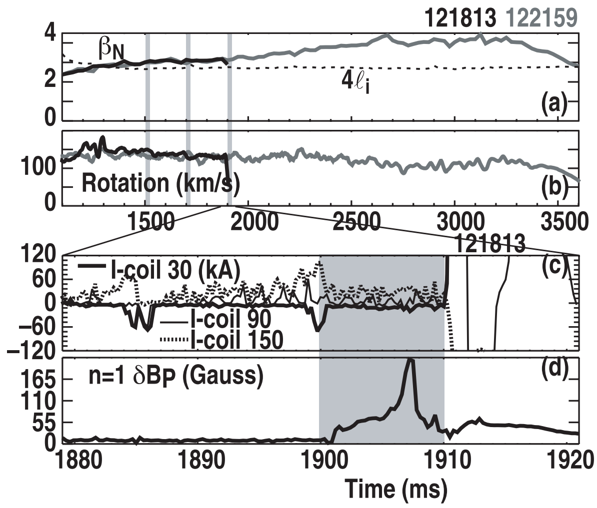

Fig. 2. Comparison of the time evolution of (a) β_N and (b) the toroidal rotation for a discharge with RWM feedback gated off at the vertical gray bands (black traces) and a discharge with continuous RWM feedback (grey traces). Also shown are the expanded time ranges for the discharge in black of (c) the I-coil currents, and (d) the *n*=1 amplitude of the RWM measured by poloidal field probes at the outboard midplane.

The new DIII-D capability of near-balanced beam injection in 2006 will allow more systematic tests of RWM feedback control in plasmas with variable plasma rotation. Experiments with near-zero plasma rotation could provide data for more straightforward comparisons to feedback modeling results, and for extrapolations to the more pessimistic predictions for the ITER steady-state scenario, where the plasma rotation alone is insufficient for RWM stabilization.

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