GA–A26050

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MAY 2008

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This is a preprint of a synopsis of a paper to be presented at the 22nd IAEA Fusion Energy Conference, October 13-18, 2008, in Geneva, Switzerland, and to be published in the *Proceedings.*

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Work supported in part by
the U.S. Department of Energy
under DE-AC02-76CH03073, DE-FG03-95ER54309,
DE-FC02-04ER54698, DE-FG02-03ER83657, and DE-FG02-89ER53297

GENERAL ATOMICS PROJECT 30200
MAY 2008

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Comprehensive Control of Resistive Wall Modes in DIII-D Advanced Tokamak Plasmas

EX-S

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Comprehensive control of the resistive wall mode (RWM) is a prerequisite for achieving steady-state commercial fusion reactors based on the Advanced Tokamak concept [1]. The RWM is an ideal-kink mode branch, excited due to the finite resistivity of the external wall surrounding the plasma when beta exceeds the ideal MHD no-wall stability limit. The existence of high beta regimes stable to the RWM and above the no-wall beta limit was successfully demonstrated at low plasma rotations in DIII-D and JT-60U [2,3]. However, low rotation plasmas are prone to the onset to neoclassical tearing modes (NTMs) [4]. Furthermore, even in this rotationally-stabilized regime, the robustness of steady-state operation is not unconditionally guaranteed. DIII-D experiments have shown that MHD activity such as edge localized mode (ELM) events and fishbones can cause a sudden increase in amplitude of the RWM within 10-100 microseconds (i.e., on the quasi-MHD time scale). The plasma rotation profile changes as a result of these events and the recovery towards the stable profile takes substantial time, especially when the momentum input is limited. It is demonstrated that fast feedback can reduce the amplitude of the RWM excited by MHD events and prevent a continuous deterioration in the plasma performance. At the same time, slow feedback control is also needed to control the plasma response to error fields.

Neoclassical tearing modes ($m/n=2/1$) at low rotation were eliminated by applying electron cyclotron current drive at the $q=2$ surface [5]. High beta plasma operation regime free of NTMs and RWMs was expanded with rotation below that previously reported in [2].

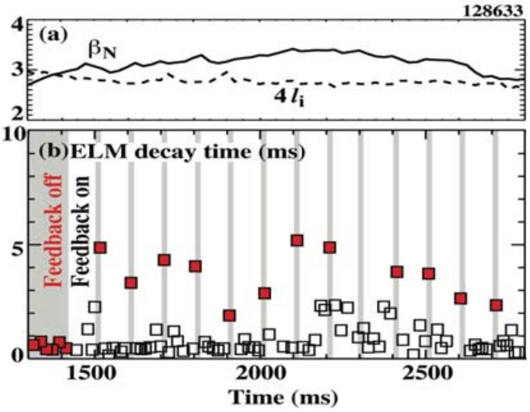

Fig. 1. In a high β_N discharge, the efficacy of feedback was monitored with repetitive short periods with feedback off. The decay time of the perturbation of up to 5 ms without feedback decreases with feedback (using simple proportional gain). Note that the long decay time occurs only when β_N exceeds the no-wall stability limit, estimated as $\beta_N = 4l_i$.

In rotationally-stabilized plasma above the no-wall stability limit, every ELM event can produce an $n=1$ RWM of 3-5 Gauss and cause a change in rotation at the $q=2$ surface by 5%-10% within a few ms, in some cases leading to collapse of rotation and β. The efficacy of feedback is demonstrated in Fig. 1 where normalized β ($\beta_N \equiv \beta aB/I$) was increased well above the no-wall limit estimated as $4l_i$, where l_i is the internal inductance. Simple feedback logic with proportional gain only is found to be sufficient to shorten the decay time of the perturbation from up to 5 ms in the high β_N phase without feedback to values of typically 1 ms with feedback. A simple model showed that the critical parameter for ELM-driven RWM growth is the RWM magnitude established during the ELM crash on the quasi-MHD time scale. The vast variation in the RWM magnitude at the ELM crash, 3-30 Gauss, is attributable as the cause of the random appearance of the β collapse.

The feedback system is most effective in controlling ELM-driven RWMs in combination with dynamic (real-time) error field compensation against residual error field, even when carefully pre-programmed error field correction has been prepared before the shot. The magnitude of the resonant field amplification (RFA) due to a weakly stable RWM evolves in time, even with a fixed external error field. Therefore, the error field correction to minimize the RFA amplitude must be adjusted in real-time. In DIII-D, two independent non-axisymmetric coils systems, one inside and the other outside of the vacuum vessel, are available. With proper feedback settings of two systems in conjunction, improved control of RFA and ELM events was demonstrated, thereby avoiding the beta collapse (Fig. 2).

Feedback at very low rotation remains a challenging task and does not always provide robust control. One such case is the onset of a slowly growing neoclassical tearing mode. Another possible limitation could arise from a loss of mode-rigidity during feedback, which has been studied using the NMA stability code [6]. It is predicted that feedback can excite a multitude of stable RWMs that couple to the original unstable RWM. This causes the mode structure, especially the patterns of the eddy currents on both the resistive wall and the plasma to deform during the feedback process. The non-rigidity is substantial when the plasma beta is high and the feedback coils are located outside of the vacuum vessel (Fig. 3). Non-rigidity is minimized by optimizing the coupling of the feedback coils to the primarily unstable RWM. The relevance of this phenomenon to ITER is studied for various proposed alternative feedback coil configurations.

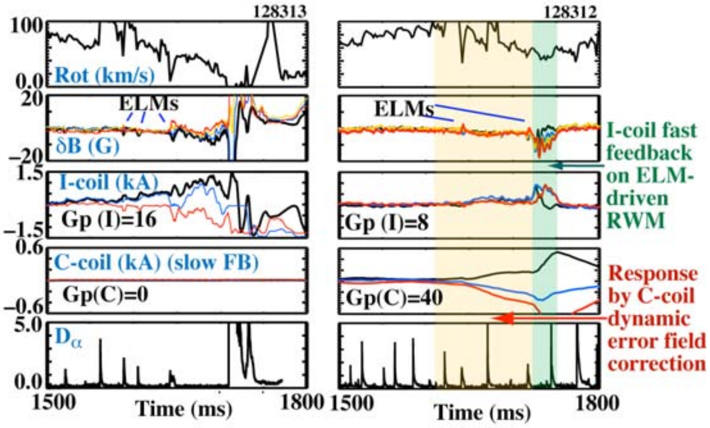

Fig. 2. While a feedback system with a fast response only (internal I-coil) fails to avoid the rotation (and β) collapse caused by ELM-driven RWMs (a-e), the combination of two feedback systems with slow real-time error field correction (external C-coil) and fast feedback (internal I-coil), can sustain the discharge (f-j).

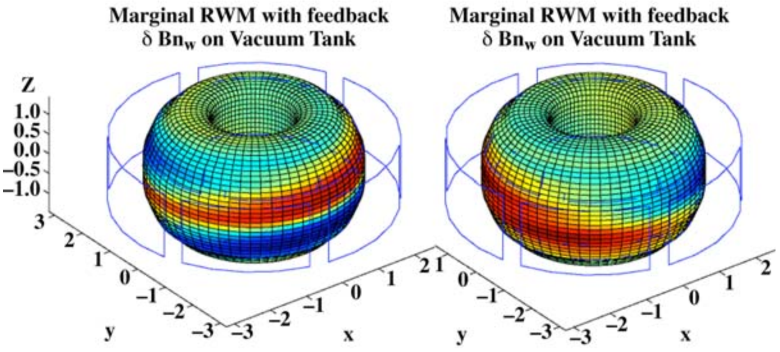

Fig. 3. An example of inefficient feedback configuration. Using external C-coil feedback at high β results in large changes to the mode structure. The helicity switches from being positive to negative as β varies from (a) just above the no-wall limit to (b) just below the ideal-wall stability limit.

This work was supported in part by the US Department of Energy under DE-AC02-76CH03073, DE-FC02-04ER54698, DE-FG02-03ER83657, and DE-FG02-89ER53297.

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