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Exploring Robustness of Magnetic Feedback Stabilization On Current-Driven Resistive Wall Mode Stabilization

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The highly-reproducible current-driven resistive wall mode (RWM) was explored to assess the RWM physics and magnetic feedback capability. Application of feedback with sufficiently-high gain can robustly stabilize the q_{95} ~ 4 current-driven RWM. Feedback stabilization needs a response time of ~1 ms, faster than the mode growth time of 3–4 ms. We have identified the feedback stabilization process as direct feedback rather than error field correction.

Current-Driven RWM

The current-driven RWM is an ideal MHD kink surrounded by a resistive wall and is excited when plasma current density gradient near the plasma surface exceeds a critical value [1]. The mode structure on the plasma surface is expected to be similar to the pressure-driven RWM. The physics of interaction between the plasma mode and the wall should be similar to the pressure driven cases. The current driven mode has been identified in tokamak experiments and used for active feedback experiments [2]. RWM feedback control in RFP has been demonstrated [3].

The ohmic current-driven RWM can be excited during the plasma current ramp in the initial plasma startup phase without neutral beam injection (NBI) heating. Figure 1 (left column) shows a typical q_{95} ~ 4 current-driven RWM observed in this series of experiment. The current-driven RWM was excited around t = 440 ms [Fig. 1(a)]. The external δB_p (poloidal field) toroidal sensors array showed little mode rotation early on [Fig. 1(e)] at the mode onset when q_{95} was near 5 and q_0 was just above 2 [Fig. 1(i)]. The RWM transforms into a rotating mode propagating in the electron drift direction around 470 ms. According to internal electron cyclotron emission (ECE) measurements, the perturbed δT_e profile shows a radial phase inversion near q=2 (ρ ~ 0.3) around t = 470 ms when the mode rotation begins, suggesting that a small magnetic island exists at q=2 even with δB_p < 5 Gauss. The $\delta T_e(\rho)$ phase inversion radius shifts outward as q_{95} decreased. The maximum amplitude in the rapid rotation phase occurs when the q=2 surface comes closer to the wall. These mode characteristics are consistent with a resistive wall tearing mode (RWTM) as categorized by Betti [4].

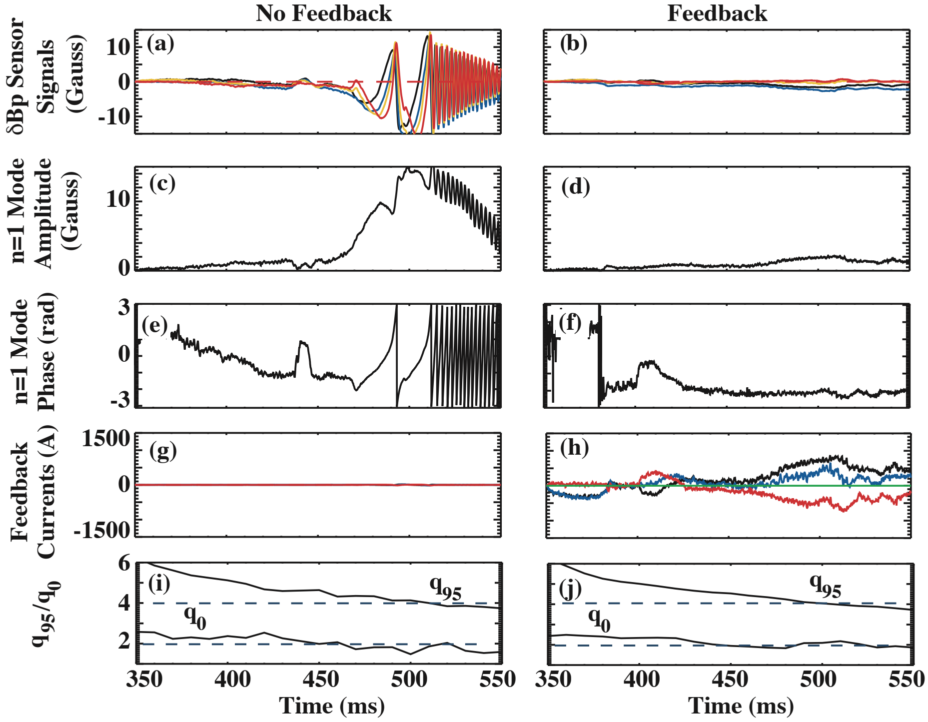

Fig. 1 current-driven RWM onset (left column) and the feedback suppression (right column). The first row (a,b): δB_p sensor signals, second row (c,d): the mode amplitude, the third row (e,f) mode toroidal phase, the forth row (g,h) feedback I-coil currents, and the fifth row (i,j): safety factor near edge q_{95} and at magnetic axis q_0. Equilibrium was calculated based only on magnetic signals.

Feedback Stabilization Suppressing the RWM Formation

When feedback with sufficiently-high gain was applied, the amplitude of the RWM did not grow and the mode coupling process to a RWTM was prevented. Figure 1 (right column) shows the feedback results with the proportional gain $G_p = 80$ and derivative gain. The choice of derivative gain was made to minimize the phase lag due to the feedback coil impedance. The required coil currents behavior [Fig. 1(h)] shows two unique features with slowly and rapidly responding components. The fast component is required for stabilizing the RWM onset. The slow component cancels out the plasma response to uncorrected error field when q_{95} approaches ~4. In this feedback-stabilized condition, the plasma mode is still actively responding to uncorrected error fields. This slow feedback current increase up to 500 ms is the dynamic error field correction. Figure 2 summarizes the feedback performance, where the mode amplitude at the $q_{95} \sim 4$ (at $t \sim$ 500 ms) is plotted vs. gain. The increase of proportional gain reduced the mode amplitude down to ~2 Gauss. The addition of derivative gain was effective in suppressing the mode amplitude even with smaller gain ($G_p = 40$). With lower proportional-gain only ($G_p = 40$), the mode amplitude was not suppressed and eventually a transition was made to the RWTM.

Clear Demonstration of Direct Feedback

In previous studies of the pressure-driven RWM, there has always been the possibility that error field correction by slow-time feedback played a dominant role. To identify the role of feedback, various preprogrammed waveform of the coil currents have been explored for these reproducible current-driven RWMs. Figure 3 shows an example with preset feedback coil currents based on direct feedback currents from a previous discharge where the RWM was feedback-stabilized. (Here the preset wave forms ware prepared by taking averages over 1 ms of the currents). If the feedback was not applied, even with these preprogrammed feedback-simulated current waveforms, the RWM was excited with fast growth rate. This clearly demonstrates that the direct feedback is needed for RWM suppression, and cannot be replaced by simple error field correction alone. There exist other evidences of direct feedback demonstration. One is shown by the advantage of time derivative gain, as discussed in the previous section. Another is the requirement of a feedback system response time less than 5 ms for robust stability indicates inadequacy of error field correction alone to stabilize the RWM.

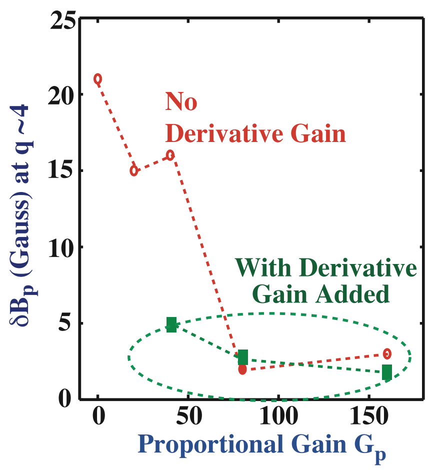

Fig. 2. The mode amplitude at the time with $q_{95} \sim 4$ vs. proportional gain G_p, and G_d = derivative gain.

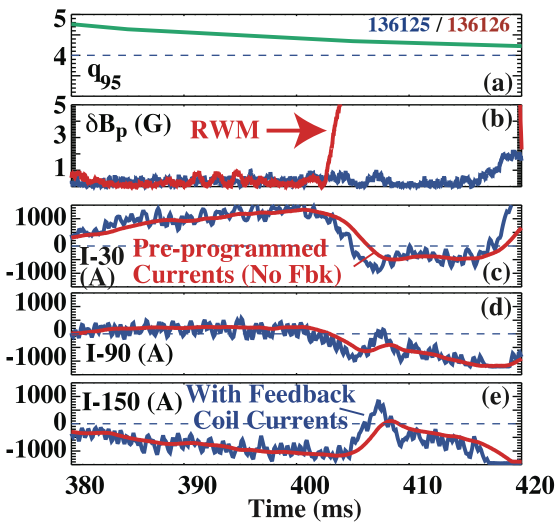

Fig. 3. Demonstration of direct feedback, (a) q_{95}, (b) the mode amplitude with/without feedback, (c-e), coil current with feedback vs. preprogrammed-coil current without feedback.

Required Feedback Response Time and Additional Fast Mode Appearance

One key parameter for feedback, the system response time, was scanned by varying the feedback bandwidth τ_p from 50 μs to 10 ms as shown in Fig. 4.

Without feedback [Fig. 4(a)], the mode grew with the time constant of 3–4 ms. With fast feedback (τ_p = 50 μs), the feedback suppressed the RWM [Fig. 4(e)]. With τ_p = 1 ms, $<\tau_w$ ~2 ms, the RWM was stabilized, but a low frequency oscillatory mode appeared around 300–600 Hz [Fig. 4(d)]. It seems the RWM closed-loop feedback system has at least two branches, one with the main unstable RWM that can be suppressed, and another mode near 300–600 Hz. According to the theoretical prediction of pressure-driven RWMs, the low frequency oscillatory mode could be related to a second least stable mode [5–7]. Experimentally, it is possible to investigate the possibility of a second least stable mode by use of active MHD spectroscopy. Preliminary results show that a plasma response does exist around 400 Hz, suggesting that a 2nd least stable mode may exist.

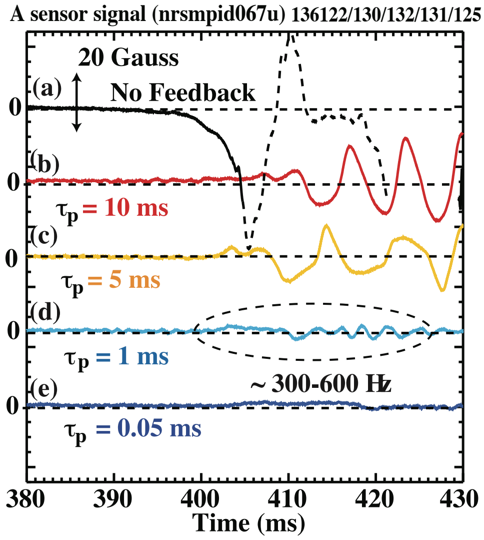

Fig. 4. The RWM suppression with various bandwidth parameters.

Discussion on Possible Feedback Process

An interesting question arises how the feedback process functions successfully on the condition where the magnetic island is on the brink of growth. One hypothesis is that after initial RWM formation, the feedback reduces the RWM amplitude and the conversion to the RWTM is suppressed. Another possibility is that the small magnetic island is excited continuously near $q \sim 2$, but the feedback reduces the RWM growth and the RWM does not couple to the small magnetic island excited near the plasma center. Further analysis of internal structure is in progress.

Summary

The magnetic feedback can provide robust stabilization for the $q_{95} = 4$ current-driven RWM. Without the magnetic feedback, the RWM transforms to the RWTM. For effective feedback, a time response faster than the mode growth time is needed. Stabilization requires direct feedback rather than error field correction. The appearance of a 300–600 Hz oscillation during feedback indicates that a 2nd least stable mode could be present, as predicted by theory. This work was supported in part by the US Department of Energy under DE-AC02-09CH11466, DE-FG02-06ER84442, DE-FC02-04ER54698, and DE-FG02-89ER53297.

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