# Global Mode Control and Stabilization for Disruption Avoidance in High-β NSTX Plasmas*

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Global MHD instabilities may potentially disrupt operation of ITER. The National Spherical Torus Experiment (NSTX) has previously investigated passive stabilization [1] and demonstrated active control [2] of resistive wall modes (RWMs), accessing high $\beta_N$ = 7.2. Current research focuses on greater understanding of the stabilization physics and how it will project to future devices, quantitative comparison to experiment, and demonstration of improved active control techniques that can reduce disruptions in those devices. This work advances the understanding necessary to aid the goal of disruption avoidance in ITER.

Combined radial ($B_r$) and poloidal ($B_p$) field sensor feedback gain and phase were scanned in NSTX experiments to produce significantly reduced $n$ = 1 field and improved stability. The disruption probability due to unstable RWMs was reduced from 48% in initial low $l_i$ experiments to 14% with this control, and remarkably, the reduced disruption probability was observed mostly at high $\beta_N/l_i$ > 11. Greater instability at lower $\beta_N/l_i$ is consistent with computations (shown later) indicating a decrease of kinetic stabilization with plasma rotation between stabilizing resonances. The fast (2-3 ms) RWM growth was found to be controlled by $B_p$ feedback, while $B_r$ feedback controlled slower $n$ = 1 field amplification. Time domain analysis of active control with the VALEN code reproduces the experimental dynamics of the mode as a function of feedback phase and determines the optimal gain.

A new model-based RWM state space controller (RWMSC), which includes a 3D model that compensates for plasma and mode-induced wall currents, was used at high $\beta_N$ in NSTX. One potential advantage of such a system is to allow for the effective use of shielded control coils, as will be available in ITER [3]. The full 3D model with more than 3000 states, including the physical mode eigenfunction near marginal stability consistent with the kinetic stability model, is reduced using a balancing transformation to less than 20 states. Open-loop

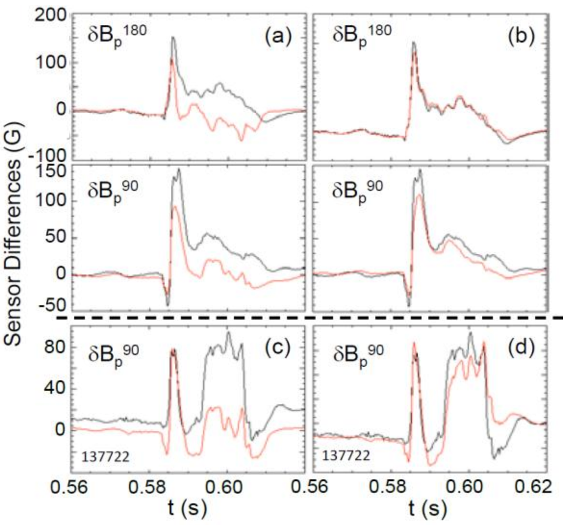


*Fig. 1: Open-loop comparison of RWM sensor subset with RWMSC observer: a) 2 states, b) 7 states, c) without, and d) with the inclusion of the NBI port (7 states).*

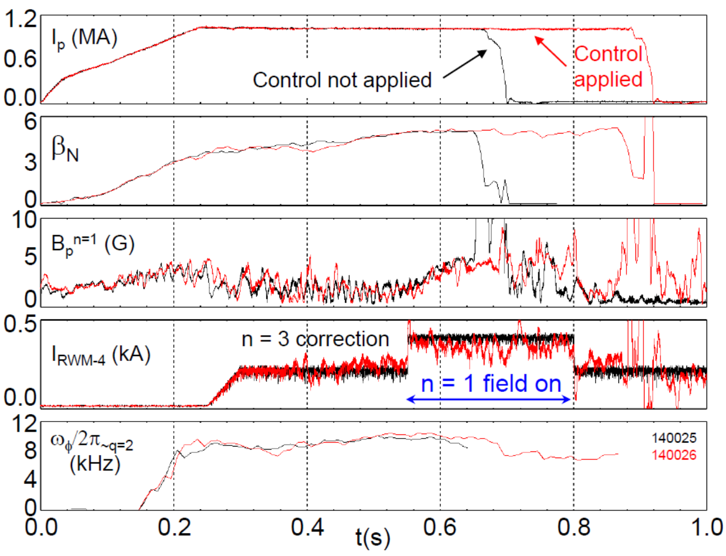


*Fig. 2: High $\beta_N$ NSTX plasma utilizing RWM state space control to survive an otherwise disruptive perturbation.*

comparisons between sensor measurements and the RWMSC model showed agreement with a sufficient number of states and improved agreement when details of the 3D wall model (including NBI ports) were added (Fig. 1). The RWMSC allows for $n > 1$ control through inclusion of $n > 1$ eigenfunctions. Control was demonstrated to sustain long pulse, high $\beta_N$ discharges with $n = 1$ fields applied that normally disrupt the plasma (Fig. 2). Plasmas limited only by coil heating constraints have exceeded $\beta_N = 6.4$, and $\beta_N/l_i = 13$. Physical effects of varying the covariant gain matrix and feedback phase are experimentally examined.

Quantitative comparisons between experiment and recent developments of kinetic RWM stabilization theory are made using further development of the MISK code. Present calculations show close quantitative agreement with NSTX experimental marginal stability points at very high $\beta_N \sim 6$, and ratio of $\beta_N/l_i$ exceeding 13 (where $l_i$ is internal inductance) (Fig. 3). Previous theories could not explain experimental results across various present devices, however more recent kinetic theory has generally shown good agreement. This new understanding leads to new expectations of RWM stability in future devices. In particular, the lack of a simple critical threshold rotation velocity was demonstrated; high or low rotation can stabilize the mode through resonance with different particle motions, while intermediate rotation between these resonances can have reduced stability (Fig. 3). Energetic particles have been shown to be generally stabilizing, but the magnitude of the stabilizing effect depends on the generally anisotropic distribution of the particles. Collisions have competing effects: they both dissipate the mode energy and damp the stabilizing kinetic effects; the low collisionality of future machines, such as NSTX-U, can improve RWM stability, but only if the plasma rotation is in a favorable resonance [1]. At low collisionality, the plasma stability gradient increases as a function of rotation. This emphasizes the utility and need for rotation and RWM control in lower collisionality devices. Scaling of the model to ITER high performance discharges indicates that the stabilizing effects of alpha particles will be required to maintain RWM stability across a wide range of expected plasma rotation profiles (Fig. 4).

Alterations to the theory now focus on improved agreement with experiment over the entire database. One such alteration is the inclusion of anisotropic distribution functions for thermal or energetic particles from neutral beam injection, which results in a correction to the pressure-driven ballooning fluid destabilization term and kinetic effects. The physics included in the MISK code is currently being benchmarked through comparisons with experiments and with other codes, such as MARS-K (Y.Q. Liu) and HAGIS (I.T. Chapman), through the ITPA MHD Stability Group Joint Experimental Analysis Task MDC-2. The relevant frequencies and eigenfunctions match between codes, and the numerical approach to the frequency resonance fraction energy integral taken in MISK has been shown to be equivalent to analytical limits.

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[1] J. Berkery, S. Sabbagh, R. Betti, et al., Phys. Rev. Lett. **106**, 075004 (2011).
[2] S.A. Sabbagh, R.E. Bell, J.E. Menard, et al., Phys. Rev. Lett. **97**, 045004 (2006).
[3] O. Katsuro-Hopkins, J. Bialek, D. Maurer, and G. Navratil, Nucl. Fusion **47**, 1157 (2007).

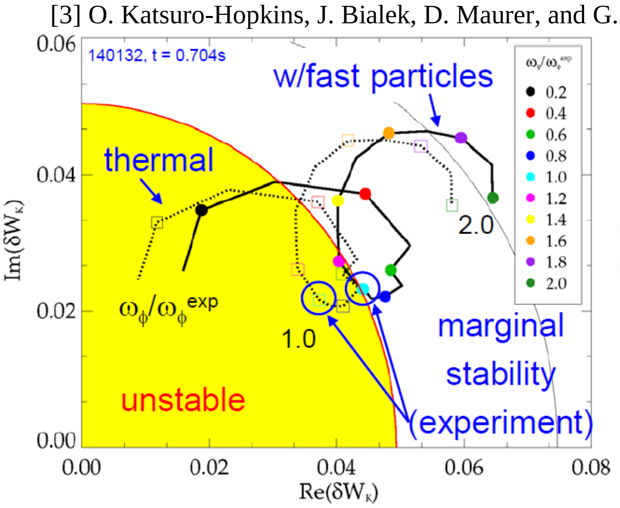


*Fig. 3: Contours of MISK-calculated RWM growth rate for high $\beta_N$, low-$l_i$ NSTX shot 140132 at 0.704s with scaled plasma rotation.*

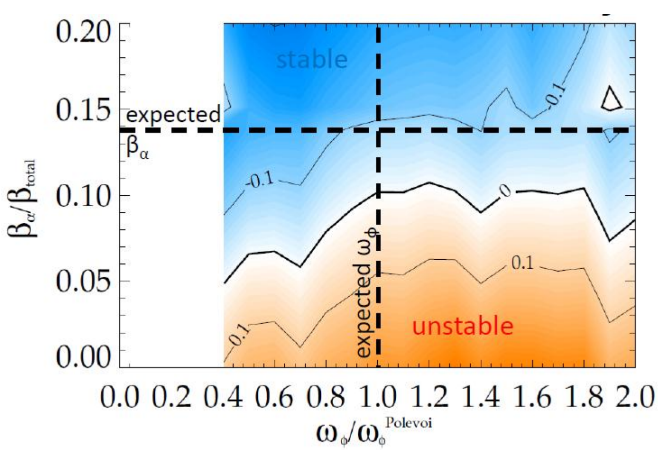


*Fig. 4: RWM growth rate contours calculated with MISK vs. rotation and alpha particle $\beta$ for ITER.*