Resistive Wall Mode Stabilization and Plasma Rotation Damping Considerations for Maintaining High Beta Plasma Discharges in NSTX*

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Maintaining steady fusion power output at high plasma beta is an important goal for future burning plasmas such as in ITER advanced scenario operation and the Fusion Nuclear Science Facility (FNSF) [1]. Research on the National Spherical Torus Experiment, NSTX, is investigating the stability physics and control to maintain steady high plasma normalized beta, $\beta_N \equiv 10^8\langle\beta_t\rangle aB_0/I_p > 5$ ($\beta_t \equiv 2\mu_0\langle p\rangle/B_0^2$) with minimal fluctuation. As ITER and FNSF span a wide range of plasma toroidal rotation, ω_ϕ, from low to high, and lower collisionality, ν, stability physics needs to be understood in these regimes. Present research addresses operation at steady, high β_N with combined improved n = 1 resistive wall mode (RWM) and newly-implemented β_N feedback control at varied ω_ϕ, the physics of experimentally observed RWM destabilization at intermediate ω_ϕ, including the effects of energetic particles (EP) and ν, and analysis of multiple RWM eigenmodes at high β_N. The physics of non-resonant ω_ϕ damping by 3-D fields [2], a candidate for rotation control actuation in devices with strong momentum input, is investigated versus ω_ϕ. Applications to ITER are made throughout.

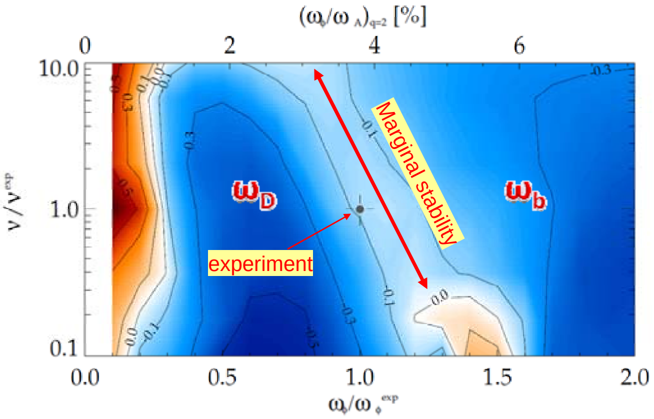


Fig. 1: RWM growth rate contours normalized to wall current decay time, $\gamma\tau_w$, for marginal plasma.

Understanding and maximizing passive RWM stabilization by ω_ϕ and energetic particles (EPs) will reduce demands on active control systems, potentially allowing control coils to be moved away from regions of high neutron flux in future devices. The intriguing observation of RWM instability in NSTX [3] at ω_ϕ levels significantly above those reported in DIII-D [4] indicates that further physics understanding is required to confidently extrapolate RWM stability to future devices. Recent analysis of the RWM stability criterion for NSTX plasmas adding kinetic dissipation effects [5] using the MISK code shows a region of reduced RWM stability for marginally stable NSTX plasmas (Fig. 1). Reduced stability is caused by ω_ϕ falling between the stabilizing ion precession drift and bounce resonances. The figure also illustrates the dependence of the reduced stability on ν, an important consideration for extrapolation to future devices. Experiments varying the EP content show their effect to be stabilizing. Calculations for ITER scenario IV show that the inclusion of isotropic alpha particles is required for RWM stabilization at β_N = 3. Improvements to MISK, including anisotropic distribution of energetic particles, are being implemented to produce a unified physics model that quantitatively reproduces RWM stability in NSTX, DIII-D, and JT-60U. Analysis shows weaker EP effects in NSTX due to reduced EP population in the outer plasma.

Non-resonant NTV braking by applied 3-D fields could be used to actuate plasma rotation control in devices heated by uni-directional NBI (e.g. FNSF) to avoid ω_ϕ levels and profiles unfavorable for RWM stability discussed above. Understanding the behavior of NTV braking vs. ω_ϕ is important for its eventual use in a rotation control system. The NTV braking torque, τ_{NTV}, that should scale as $|\delta\boldsymbol{B}|^2\omega_\phi$, where $|\delta\boldsymbol{B}|$ is the applied 3-D field magnitude, has produced predictable, controlled changes to ω_ϕ in NSTX. Recent experiments have varied the ratio of ion collisionality to the ExB frequency, ω_E, a key parameter that determines the scaling of NTV with ν_i in the collisionless regime ($\nu_i^* < 1$) [2]. As $|\omega_E|$ is reduced, τ_{NTV}/ω_ϕ is expected to scale as $1/\nu_i$ when $(\nu_i/\varepsilon)/(nq|\omega_E|) > 1$ and maximize when it falls below the ∇B

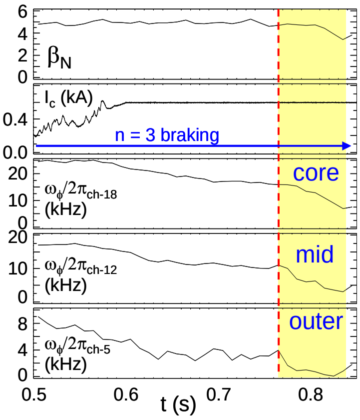
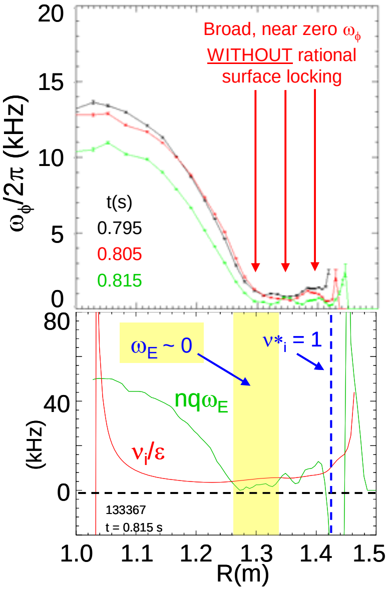


Fig. 2: Increased non-resonant magnetic braking at fixed applied field and β_N at low ω_E.



drift frequency and enters the superbanana plateau regime [6]. Lithium wall preparation was used to suppress resonant braking and mode locking due to NTMs, allowing the investigation of non-resonant NTV braking down to low values of ω_ϕ and $|\omega_E|$. This regime is also most relevant for application to ITER. Increased braking strength was observed at constant $|\delta \boldsymbol{B}|$ and β_N in experiments when ω_ϕ (and $|\omega_E|$) were sufficiently decreased, as expected by NTV theory (Fig. 2).

The influence of multiple RWM eigenfunctions on RWM active control, including the stable mode spectrum, is a potential cause of β_N fluctuation and loss of control. Observations and analysis show evidence of driven RWM activity in NSTX high β_N experiments. The newly-developed multi-mode VALEN code is being applied to these experiments to determine if the computed mode spectrum correlates with observations. The multi-mode response is theoretically computed to be significant in these plasmas when $\beta_N > 5.2$. The computed RWM growth rate vs. β_N is in the range observed in experiment. The computed spectrum of modes comprising the perturbed field is shown in Fig. 3. Using this model, multi-mode RWM stability is determined for ITER plasmas with elevated q_0 and β_N sufficient to destabilize $n = 2$ modes.

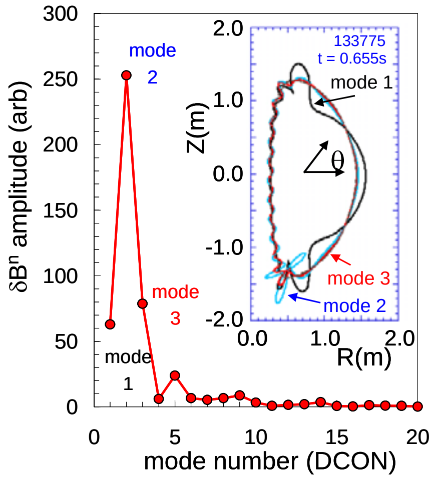


Fig. 3: Computed eigenfunction spectrum of the perturbed field in multi-mode RWM analysis.

Combined $n = 1$ RWM and β_N feedback was used to generate high pulse-averaged β_N with low levels of fluctuation. NTV braking was used to vary ω_ϕ. This braking mechanism (shown in NSTX to increase with ion temperature, consistent with a $T_i^{5/2}$ dependence expected by theory) is compatible with β_N feedback to produce steady ω_ϕ. A comparison of two long pulse discharges at significantly different ω_ϕ is shown in Fig. 4. Experiments in 2010 will examine steady long-pulse operation at further reduced ω_ϕ for comparison to ITER, enhanced $n = 1$ RWM control with radial field sensors, better AC compensation, and advanced RWM control using a state-space algorithm to compensate for the effect of conducting structures on the control fields [7].

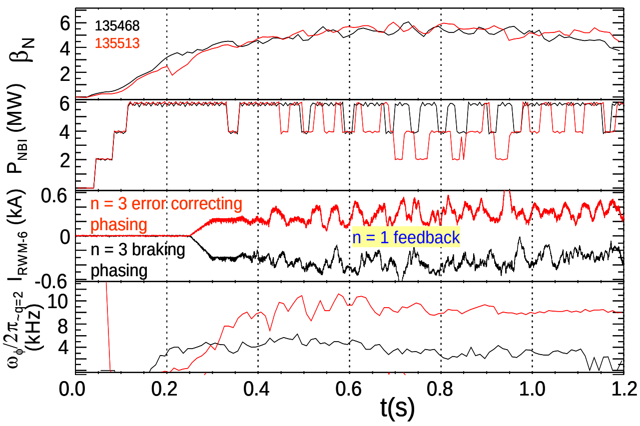


Fig. 4: Maintenance of β_N with low fluctuation at various ω_ϕ by use of n = 1 and β_N feedback.

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