RWM stabilization and maintenance of high beta plasmas 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 a spherical torus component test facility (CTF) [1]. Plasmas in the National Spherical Torus Experiment (NSTX) have exceeded plasma normalized beta, $\beta_N \equiv 10^8\langle\beta_t\rangle aB_0/I_p = 7$ transiently ($\beta_t \equiv 2\mu_0\langle p\rangle/B_0^2$). Present research investigates the stability physics and control to maintain steady high β_N greater than 5 with minimal fluctuation. As ITER and CTF span a wide range of plasma toroidal rotation angular frequency, ω_ϕ, from low to high, stability physics needs to be understood in these regimes. Variation of ω_ϕ is also critically important in this study, as it has been recently found that resistive wall modes (RWM) can become unstable at ω_ϕ levels far greater than previously reported in tokamaks [2], and that stability depends on ω_ϕ profile resonances [3,4]. Additional considerations at high β_N, such as experimental indication of multiple resistive wall eigenmodes that may effect control, are investigated.

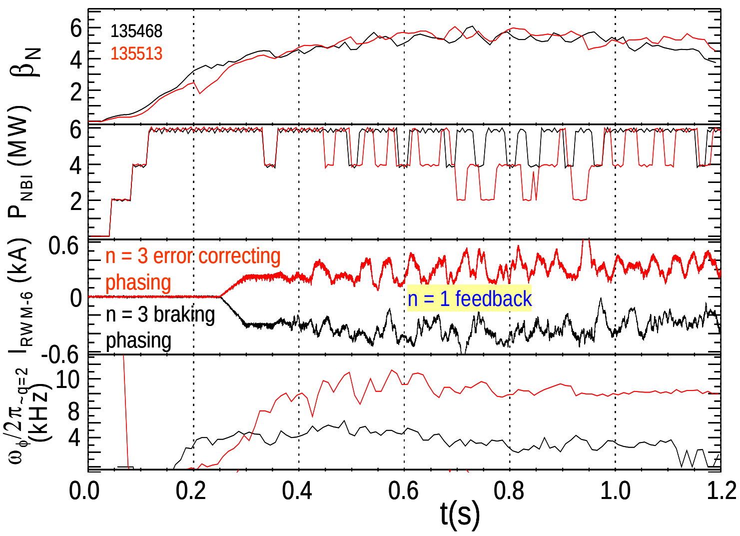
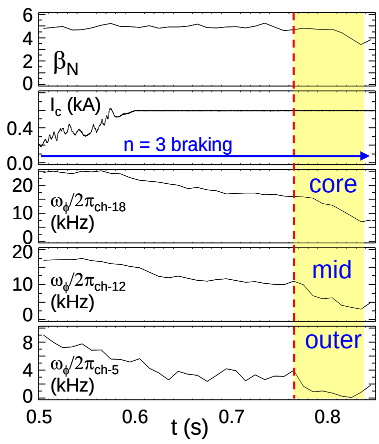


Fig. 1: Maintenance of β_N with low fluctuation at various ω_ϕ by use of n = 1 and β_N feedback, and n = 3 NTV braking.

Combined $n = 1$ resistive wall mode control and newly-implemented β_N feedback control were used to generate high pulse-averaged β_N with low levels of fluctuation at various levels of plasma rotation. A key motivation in performing this experiment was to understand the interaction of the two control systems as plasma rotation was varied by applying different levels of n = 3 non-resonant magnetic field.

A comparison of two successful long-pulse discharges using both n = 1 RWM feedback and β_N control at significantly different levels of plasma rotation is shown in Fig. 1. Non-resonant magnetic braking by applied 3D fields due to neoclassical toroidal viscosity (NTV) [5] was used to vary ω_ϕ [6]. Producing steady ω_ϕ using this drag mechanism (shown in NSTX to increase with ion temperature, consistent with a $T_i^{5/2}$ dependence expected by theory [4]) is shown to be compatible with β_N feedback. The discharge with higher ω_ϕ has higher plasma energy confinement time, and therefore requires lower NBI power to maintain constant β_N. Steps in NBI power are created by feedback control to maintain constant β_N, but not to maintain plasma rotation. Despite this, ω_ϕ reaches an approximate steady state near q = 2 in these plasmas (Fig. 1). Increasing NBI heating increases the momentum input, as well as increasing plasma β_N and T_i. Increasing β_N increases both the plasma amplification of the applied field (although small for n = 3 fields) and T_i. Each of these leads to an increase in NTV braking torque. Therefore as NBI power varies, the changes in the driving and braking torques applied to the plasma tend to offset each other, producing steady plasma rotation.

As mentioned above, NSTX research has shown that RWM instability can occur at relatively high toroidal rotation levels. MISK code analysis, which computes the perturbed mode energy including kinetic effects, shows a region of reduced RWM stability caused by the rotation falling between stabilizing ion precession drift and bounce resonances [3]. Recent MISK analysis has included the influence of fast-ions on RWM stability [7]. These calculations, along with dedicated experiments on NSTX, show that the RWM becomes progressively more stable as fast-ion pressure is increased, but that the variation of ω_ϕ has a larger effect on the RWM growth rate than do the fast particles. This result can explain why the RWM can become unstable in NSTX as ω_ϕ is varied at relatively high levels, while a similar result is not found in devices such as DIII-D, where the effect of the fast particle population on RWM stability is larger. Similar MISK analysis



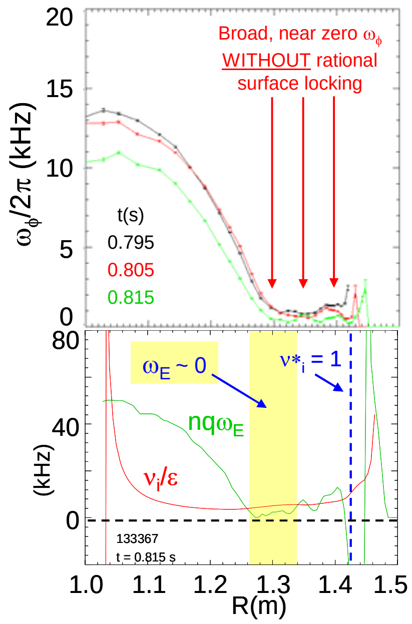


Fig. 2: Increased non-resonant magnetic braking at fixed applied field and β_N at low ω_E.

was applied to ITER advanced scenario IV plasmas to determine the relative importance of ω_ϕ and fast particles in RWM stabilization. The expected level of rotation in ITER is insufficient for mode stability. However, the alpha particle population expected in ITER can stabilize the RWM at the tested value of $\beta_N = 3$ (ideal no-wall limit = 2.5).

Non-resonant NTV braking by applied 3-D fields can be used to actuate plasma rotation control for future devices driven by uni-directional NBI (e.g. CTF) 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 scales 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 ($\nu_i^* < 1$) [8]. 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 drift frequency and enters the superbanana plateau regime [9]. 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 $|\omega_E|$ near zero. 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 (Fig. 2).

In high β_N plasmas, the influence of multiple RWM eigenfunctions on n = 1 active

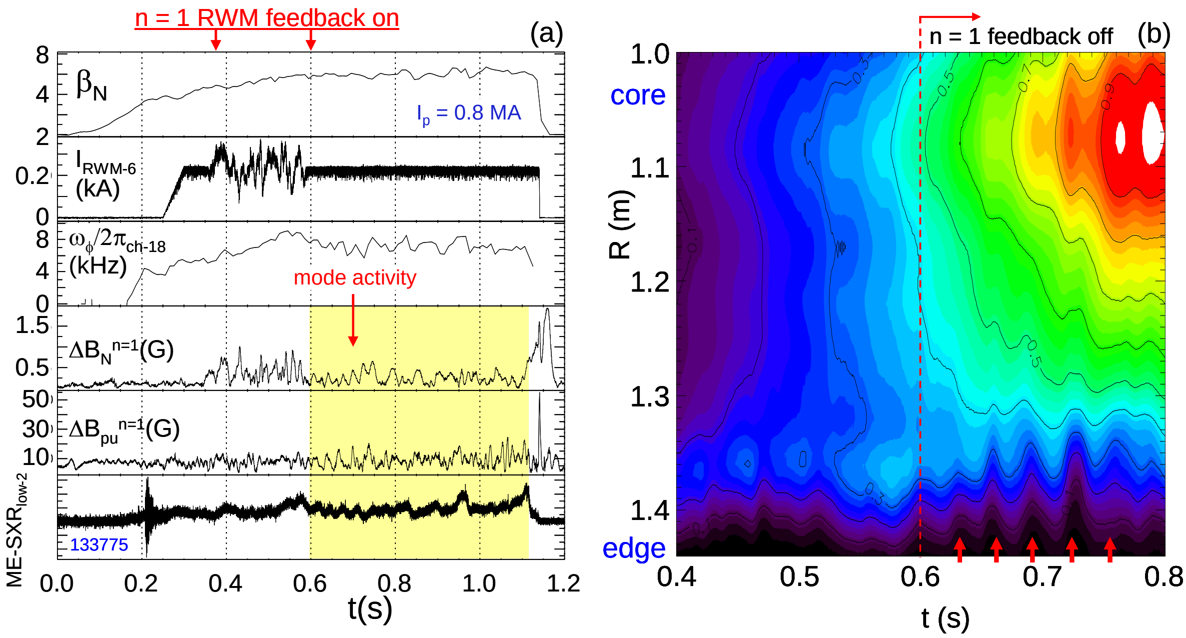


Fig. 3: (a) Evolution of high β_N plasma and low frequency mode activity with n = 1 control turned off (b) Time evolved radial reconstruction of multi-energy soft X-ray emission.

feedback, including the stable mode spectrum, is a potential cause of β_N fluctuation and loss of control. Therefore, detection and understanding of such modes is important. Fig. 3 illustrates mode activity in both the n = 1 RWM magnetic sensor amplitude, and a multi-energy soft X-ray diagnostic [10] when n = 1 mode control is turned off. The fluctuation frequency of about 30 Hz is in the RWM frequency range and is too slow to be a rotating kink or tearing mode (which would rotate at least as fast as the local plasma rotation, > 1 kHz). The mode activity appears driven, or saturated, as an unstable RWM would have a fast growth time of less than 10 ms at $\beta_N \sim 6$. This activity causes fluctuations in both β_N and plasma rotation (Fig. 3). The newly-developed multi-mode VALEN code has been applied to these experiments to determine the mode spectrum. The multi-mode response is theoretically computed to be significant in these plasmas when $\beta_N > 5.2$. The computed RWM growth time vs. β_N is in the range observed (Fig. 4). The computed spectrum of modes comprising the perturbed field (4c) shows that the second least stable mode has dominant amplitude, and is largest near the lower divertor. Similar calculations for ITER scenario IV plasmas with elevated q_0, β_N = 4, and a modeled blanket conducting structure show a spectrum with significant amplitude for three n = 1 modes and two n = 2 modes.

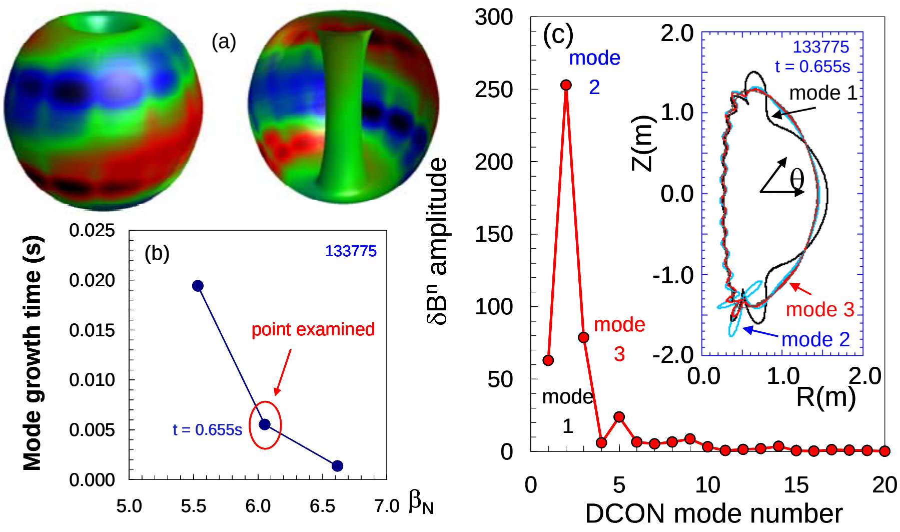


Fig. 4(a) δB_{normal} from wall currents, (b) growth time vs. β_N, (c) eigenmode spectrum of perturbation in multi-mode analysis (lower is least stable).

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