Kinetic resistive wall mode stability evaluation and physics insight application in NSTX

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Research on the National Spherical Torus Experiment (NSTX) has studied the stability of global modes such as resistive wall modes (RWMs) in high-beta fusion plasmas for disruption avoidance. Stabilizing mechanisms for RWMs have been identified as the transfer of energy from the mode to thermal particles through rotational resonances [1, 2] and the effect of energetic particles to resist distortion of the magnetic field lines [3]. These kinetic effects have been theoretically developed, implemented in calculations with the `MISK` code, and compared favorably with NSTX experiments including prediction of the marginal stability point [1].

Additionally, agreement has been found between the kinetic RWM stability model and the trends of resonant field amplification (RFA) measurements made using low-frequency MHD spectroscopy in NSTX [4]. Observations from previous NSTX resistive wall mode (RWM) active control experiments and the wider NSTX disruption database indicated that the highest β_N plasmas were not the least stable. In recent experiments, stability was measured to increase at β_N/l_i higher than the point where disruptions were found [4]. This favorable behavior was shown to correlate with kinetic stability rotational resonances, and an experimentally determined range of measured $E\times B$ frequency with improved stability was identified [4]. RFA amplitude, a measure of proximity to instability, increased for plasmas with ω_E above and below the range of expected stabilizing precession drift resonance. Additionally, stable plasmas appeared to benefit further from reduced collisionality, in agreement with expectation from kinetic RWM stabilization theory.

Validated and benchmarked calculations of kinetic resistive wall mode stability are important for disruption avoidance in ITER and other high performance tokamaks by providing a confidently predicted RWM stable operating region. In Ref. [5] an ITPA MHD Stability Group joint analysis task benchmarked three leading kinetic RWM codes, `MARS-K` [6], `MISK` [7], and `PENT`

[8]. Good agreement was found between the code calculations for two Solov'ev analytical equilibria and a projected ITER equilibrium [5], including the most important stabilizing kinetic effect: resonances between the plasma rotation and frequencies of thermal particle's motion [1]. The task also demonstrated and corrected differences. For example, when using ideal MHD, integration over mode eigenfunctions near rational surfaces leads to predictions of much greater stability than is consistent with experimental marginal stability points in NSTX. Finally, several important physics considerations were not included in that effort, including: non-resonance rotational effects [9], collisions [10], and isotropic energetic particles [3]. Including these three additional pieces will present a more realistic projection of ITER stability.

Fluid rotational effects have been shown to be important modifications to the ideal wall limit [9]. Note that these rotational fluid effects are distinct from the rotational *resonance* effects that appear through consideration of kinetic effects through the perturbed pressure, and also the effect of plasma rotation on the equilibrium [11], which may be important for stability [12]. We have found that around the expected ITER rotation, the rotational terms are small and can be neglected. The effect of including collisions is to modify the calculated δW_K, especially at low rotation and primarily by reducing the electron term (the ion term is less effected), as expected [10].

In the end, we are interested in the calculated growth rate of the RWM in ITER with variations around the projected equilibrium operating point. Both MISK [3] and MARS-K [13, 14] have been previously used for this purpose. In Ref. [5] (in particular Fig. 24a), a unified, benchmarked analysis of ITER stability using a perturbative kinetic stability approach with a consistency of treatment of the rational surfaces between the codes (singular contributions at the rational surfaces have been removed [5], which was the traditional treatment in MISK, but not in MARS-K) was presented. It was found that the nominal ITER rotation profile was in an unstable range between lower rotation, where precession resonances could stabilize the mode, and higher rotation, where bounce and transit resonances could stabilize the mode. However, a very large range of scaled ω_E was used for benchmarking purposes in Ref. [5], including rotations

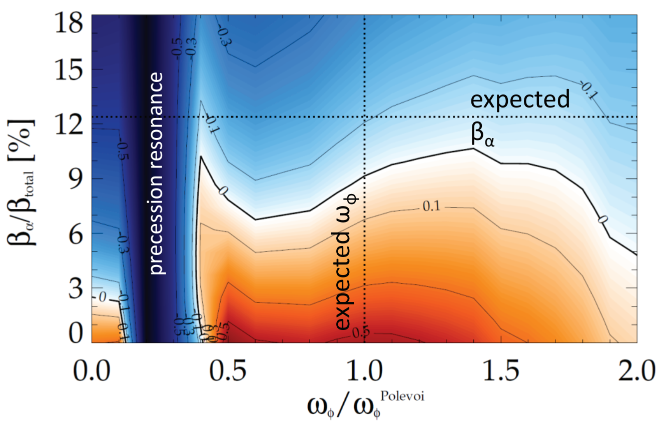

Figure 1: *Contours of calculated normalized growth rate of the resistive wall mode in ITER vs. scaled rotation profile and alpha particle beta from* MISK

orders of magnitude above the expected rotation, where fluid rotational effects become large. Here we instead scale ω_ϕ over a much smaller range, add collisionality, rotational effects, and isotropic alpha particles while also scaling $\beta_\alpha/\beta_{\text{total}}$ to present a much more realistic picture of the potential operating space of ITER around the given equilibrium. Figure shows a contour plot from MISK calculations of $\gamma\tau_w$ vs. scaled rotation and alpha particle beta. The nominal values of $\omega_{\phi 0}$ and of $\beta_\alpha/\beta_{\text{total}} \approx 12.4$ are indicated on the plot. In ITER, collisionality and rotation will both be relatively low compared to present-day devices, therefore their impacts are limited. Alpha particles, however, are shown to be critically important to the stability of the analyzed ITER scenario IV target, consistent with previous results [3].

Further improvement of the already close agreement of MISK to experimental results is also being pursued by comparison of the benchmarked code calculations to a large database of NSTX discharges and implementation of additional physics in the code, including the rotational effects on the fluid stability previously mentioned, which may be more significant in NSTX, and the effect of pressure anisotropy. Figure shows MISK calculated growth rates of the resistive wall mode in NSTX vs. scaled rotation profile for three experimentally stable cases and three experimentally marginally unstable cases, with all resonant particles included (precession, bounce, and circulating thermal ions and electrons). One can see that the code predicts instability or very close for the cases from equilibria just before the plasma goes unstable in the experiment, and predicts robust stability for the plasmas that are stable in the experiment.

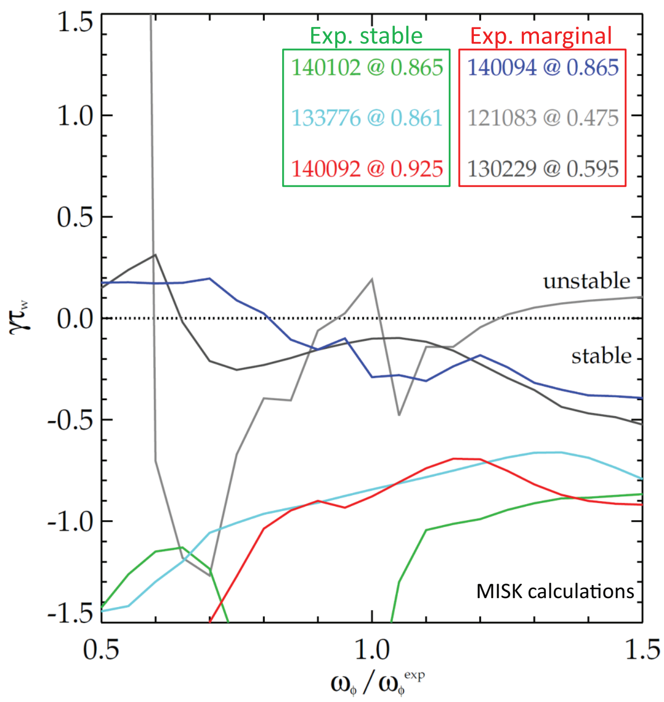

Figure 2: MISK *calculated growth rates of the resistive wall mode in NSTX vs. scaled rotation profile for three experimentally stable cases and three experimentally marginally unstable cases.*

Finally, attention is now turning to practical application of the knowledge gained by kinetic stability physics insight, calculations, and comparisons with experiment, to use in a disruption avoidance algorithm in NSTX-Upgrade. NSTX-U is projected to operate in a similar range of β_N/l_i to NSTX while potentially having considerably lower collisionality and better control over the rotation magnitude and profile (both from the new, more tangential neutral beam and from improved rotation profile control capabilities) [15]. Additionally, RWM stability has been identified as critical for high performance NSTX-U operation [15]. A system monitoring real-time measurements of plasma rotation and RFA amplitude and modeled ω_E profile (which is the important parameter for kinetic rotational resonances) could be quite useful to detect steady, relatively slow approaches toward marginal stability. Then various actuators such as non-resonant magnetic braking using neoclassical toroidal viscosity (NTV) [16] or changing neutral beam injection sources for rotation control could be used to return the plasma to a more stable state. In NSTX-U, a real-time measurement of plasma rotation will be used for rotation profile control informed by kinetic stability theory to complement active (magnetic) RWM control when either slow, controlled or sudden, uncontrolled changes take the plasma through a marginal stability point.

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