# Disruptivity Reduction Research on NSTX-U, Including Characterization of Causes and Use of Kinetic Stability Theory Models

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Near 100% disruption avoidance is an urgent need for ITER and is the present “grand challenge” in tokamak stability research. ITER must achieve a disruption rate of less than 1-2% due to energy load and halo current considerations. This is daunting, but can be achieved; JET has recently achieved < 4% disruptions with a carbon wall [1]. NSTX-U is planning a disruption handling system in which disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by massive gas injection.

The combined passive and active global mode control system described below will be an essential component of a multi-faceted research program for disruption prediction and avoidance needed for present and future tokamaks, which will include the quantitative assessment of the effectiveness of the system for disruption avoidance.

The initial approach to disruption prediction and avoidance in NSTX-U will be to characterize physics elements which lead to disruptions, such as density limits, shape control issues, approaching vertical instability, approaching global mode instability (e.g. resistive wall modes), etc... Disruption categories and their sequential connections analogous to those used on JET [2] are being adopted, with specific additions for NSTX-U. Each of the elements will have related quantitative experimental evaluations. Reduction of plasma disruptivity in NSTX-U will then require implementing reduced stability models used in real-time. The specific subject of the rest of this whitepaper is global mode stability.

Plasmas can operate stably above ideal magnetohydrodynamic limits to the pressure by dissipating the energy of the expanding magnetic field into the motions of the particles via stabilizing rotational resonances. This modification to ideal stability by kinetic effects is calculated by various codes including the MISK code [3] which has been extensively developed through theory [4,5,6,7,8] and benchmarked against other leading codes [9]. The predicted RWM growth rates have then been compared extensively to experimental results in both the National Spherical Torus Experiment (NSTX) over many years [10,11,12,13,14] and the DIII-D tokamak [15,16], and the experimental results from those two machines have been unified under a single model [17]. This theory is now accepted by the ITPA MHD Stability joint experimental task group MDC-21 as the lead theory to quantitatively determine marginal stability limits for global MHD modes.

NSTX-U [18] (the upgrade to NSTX) has new off-axis neutral beams that can potentially broaden both the current and pressure profile [19]. A broadened current profile tends to lower the no-wall and ideal-wall beta limits [20]. In contrast, a broadened pressure profile is beneficial in raising the ideal-wall beta limit [19,21], but it can lower the no-wall limit, opening up a large $\beta_N$ range in which the resistive wall mode must be passively or actively stabilized. However, modifications to ideal stability by kinetic effects and active control of resistive wall modes are expected to continue to enable passively and actively stable operation significantly above the no-wall limit in future NSTX-U experiments at lower plasma collisionality.

The MISK code has been validated by detailed comparison with experimental results from NSTX. In many discharges the code predicts a transition from damping of the mode to growth as the time approaches the experimental time of plasma disruption via an unstable resistive wall mode (RWM). These validations are important for believable projections of the stability of future devices, including ITER. The main stabilization mechanism is through rotational resonances with the motions of thermal particles in the plasma, though energetic particles can also contribute to stability, and it is when the plasma rotation falls in between these resonances that the RWMs grow in NSTX and DIII-D. Stability measurements using MHD spectroscopy of (mostly) stable NSTX plasmas have illuminated the roles of collisionality, rotation, and $\beta_N/l_i$ in RWM stability and have added support to the theory of RWM stabilization through kinetic resonances [14]. Resonant field amplification (RFA) amplitude, a direct measure of the approach to instability, increases for plasmas with ExB frequency, $\omega_E$, above and below the range of precession drift resonance.

Attention is now turning to further practical application of the knowledge gained by kinetic stability physics insight, calculations, and comparisons with experiment, to be directly used in a disruption avoidance algorithm in NSTX-U. If MISK calculations could be performed in real time, they could be used in a control system to indicate the approach of marginal stability. Of course, full MISK calculations cannot be performed in real time, but simplified model calculations informed by the physics of kinetic theory are planned for NSTX-U, and for application to future devices [14]. In future machines, the quantity $\langle\omega_E\rangle$ could conceivably be monitored by a real-time charge exchange recombination spectroscopy system that measures ion rotation, density, and temperature profiles ($\omega_E \approx \omega_\varphi + 1/(en_i)(d(n_iT_i)/d\Psi)$). Realistically, however, future devices may only have real-time measurements of $\omega_\varphi^C$ at limited radial locations, such as is planned for NSTX-U [22], in which case $\langle\omega_E\rangle$ could still be modeled in real time with modeled density and temperature profiles. A system monitoring real-time measurements of plasma rotation and RFA amplitude and modeled $\langle\omega_E\rangle$ would be used to detect steady, relatively slow (transport timescales vs. ideal MHD timescales) approaches toward marginal stability, or deviations toward positive mode growth rates in general. Then, various actuators such as non-resonant magnetic braking [23] or changing neutral beam injection sources for rotation control could be used to steer the plasma to a more stable state.

At low collisionality, however, the plasma stability gradient is expected to increase as a function of rotation [6], so the plasma could change between a stable and unstable state more quickly (~10 ms time scale in NSTX-U) as rotation is changed. Combined with frequency limitations on real-time RFA measurements, this calls into question a strategy of relying solely on real-time RFA feedback for disruption avoidance in future machines unless the technique is developed to provide stability assessment with higher frequency. This emphasizes the need for rotation profile control independent of RFA feedback and informed by kinetic stability theory and also for active (magnetic) RWM control when either slow, controlled or sudden, uncontrolled changes take the plasma through a marginal stability point. Advanced model-based, RWM state-space control of the RWM was demonstrated five years ago in NSTX to maintain stable plasmas at twice the $n = 1$ no-wall stability limit with normalized beta reaching 6.4 and normalized beta/plasma internal inductance > 13, for pulse lengths limited only by OH transformer flux [24]. This effective, physics-based, and flexible RWM active control system will continue to be operated and further expanded in capability (e.g. the inclusion of multiple mode control) for NSTX-U starting in 2015.

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