Characterization and Forecasting of Unstable Resistive Wall Modes in NSTX and NSTX-U *

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A comprehensive approach to the prevention of disruption of fusion plasmas in tokamaks, through forecasting and avoidance of the detrimental consequences, is needed for future devices which cannot tolerate disruptions such as ITER. First, it is important to identify disruption event chains and the specific physics elements which comprise those chains in present devices. Second, if the events in the disruption chains can be forecast, cues can be provided to an avoidance system to attempt to break the chain. Finally, if avoidance is deemed untenable, a mitigation system can significantly reduce disruption ramifications.

Within this framework, we examine the characterization and forecasting of unstable resistive wall modes (RWMs) in the NSTX tokamak and its upgrade NSTX-U which has presently begun operation. The RWM is a tokamak eigenmode which grows on the time scale of the penetration of the field into the surrounding wall structure, τ_w. RWMs can be common physics events in the chains leading to disruption of high beta plasmas. The RWM is identified by a variety of observations [1] including an exponential growth in the magnetic signal on low frequency magnetic sensors located between the plasma and the vacuum vessel.

If the RWM is independently identified as described above in a dataset of disruptive discharges, then for characterization purposes its timing can be determined by examining whether an exponential rise in a magnetic measurement exceeds a pre-set threshold. Otherwise, for forecasting purposes, more physics-based models can be employed for early warning of approaching marginal RWM stability. Some examples are the use of active MHD spectroscopy [2], or the mismatch between the observer of an RWM state-space controller and measured signals. Another method, which is described in detail presently, is to examine when the plasma toroidal rotation profile falls into a weaker RWM stability region based upon kinetic stability theory [1,3,4]. In all of these cases, one might then use a plasma rotation control system to avoid these unfavorable profiles, or use active control of the RWM.

The stability of plasmas to RWMs has been explained in multiple devices by employing calculations of kinetic effects [5], with codes such as MISK [3,4]. MISK solves for the growth rate of the RWM through a dispersion relation dependent on the change in potential energy due to the perturbed kinetic pressure δW_K. δW_K is calculated using the perturbed distribution function from the drift kinetic equation, and the solution involves a frequency resonance fraction $\lambda \sim (\omega_D+\omega_b-i*\nu_{eff}+\omega_E)^{-1}$, where ω_E, the *ExB* frequency, scales with the plasma rotation, which can be in resonance with the precession (ω_D) and bounce (ω_b) motions of the particles [4] and is effected by the collisionality (ν_{eff}).

A parameterized reduced model for the fluid no-wall δW term of the dispersion relation, $\delta W_{no-wall}{}^{n=1} = 2-\tfrac{2}{3}\beta_N{}^3((6.7l_i)^{-3}+(1.91p_0/<p>)^{-3}+(14(A^{-1}-0.4))^{-3})$, which depends on parameters that can be measured or modelled in real-time (l_i is internal inductance, $p_0/<p>$ is pressure peaking, and A is the aspect ratio), has been recently computed [5]. For the kinetic δW_K term, full MISK calculations cannot be performed in real time, but simplified model calculations based on physics insight from MISK calculations are being examined [2]. The model is based upon further simplification of previous analytical models for kinetic effects [6], plus the addition of the effect of energetic particles [1] on the real part of δW_K, and takes a form that depends on ω_E, ν_{eff}, and β_{EP}/β_{total}, such that $Re(\delta W_K) = c_1\beta_{EP}/\beta_{total} + F_1(\omega_E,\nu_{eff})$ and $Im(\delta W_K) = F_2(\omega_E,\nu_{eff})$. Figure 1 shows a measured average ExB frequency inside the plasma pedestal from post-discharge equilibrium reconstructions of four NSTX discharges. A level of ~3.5-5.5 kHz is associated with kinetic RWM stability from resonance with thermal ion precession drift [2]. In the experiment the discharge shown in green maintained this stabilizing rotation level and remained stable, the discharge shown in blue fell out of this range and an unstable

RWM disrupted the plasma, while those shown in red and cyan exhibited high levels of resonant field amplification, indicating near-marginal RWM stability [2].

Fig. 1: Average ExB frequency vs. time for four NSTX discharges.

The reduced kinetic model results, in terms of timing of warnings for impending RWM instability, are being tested in this work against an independently characterized NSTX database. In order to gain an understanding of the connection of physical disruption chain events including RWMs, analysis was performed on a database of 44 NSTX discharges that were pre-determined to have unstable RWMs which lead to disruptions (tearing modes were stable in these discharges). For this analysis, we have created the Disruption Event Characterization and Forecasting (DECAF) code to analyze disruptions in tokamaks. For each discharge, the code finds the chain of events leading up to that disruption by applying one or more criteria that define each of the implemented events. The grouping of physical events in DECAF modules is an automated approach analogous the manual work of deVries et al. [7] and the present approach to warning algorithms in DECAF follows Gerhardt et al. [8], with each approach being expanded in the present implementation.

A first positive result of DECAF analysis is that the RWM event was detected in all of the discharges, as were failure to meet plasma current request (IPR), full-current quench major disruption (DIS), loss of wall proximity control (WPC) and finally low edge safety factor (LOQ) warnings, which occurred near the time of disruption as the plasma was shrinking in size (see Fig. 2). Loss of vertical stability control (VSC) was present in most of the discharges (31 of 44), as was pressure peaking (PRP) (34), but PRP typically

Fig. 2: Histogram of the timing of various disruption chain events in the 44 discharge NSTX database before the time of disruption, within 70 ms.

occurred with or after the RWMs, and is therefore concluded not to have caused the RWMs.

With the RWM $B_p^{n=1}$ lower sensor amplitude threshold of 30G ($\delta B/B_0 \sim 0.67\%$) used here the RWM warning was typically found near the disruption limit (see Fig. 2). In 59% of the cases, the RWM event occurred within 20 τ_w of the time of disruption (DIS) (τ_w here is 5 ms). These RWMs lead to a collapse of β_N and plasma current (IPR) and eventually to LOQ and disruption, and thus pose a serious issue to ITER and other future devices. Additionally, the RWM warnings that occurred *earlier* than 20 τ_w were not false positives; they cause significant (~30% or more) decreases in β_N – minor disruptions. The DECAF code analysis of RWM-induced disruptions is under active development, including the forecasting and detection of minor disruptions, discrimination of rotating MHD which locks vs. RWMs which are born locked, and improved approaches to determine causality in disruption event chains.
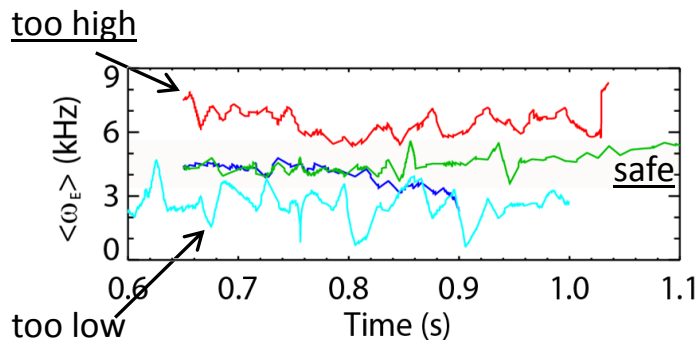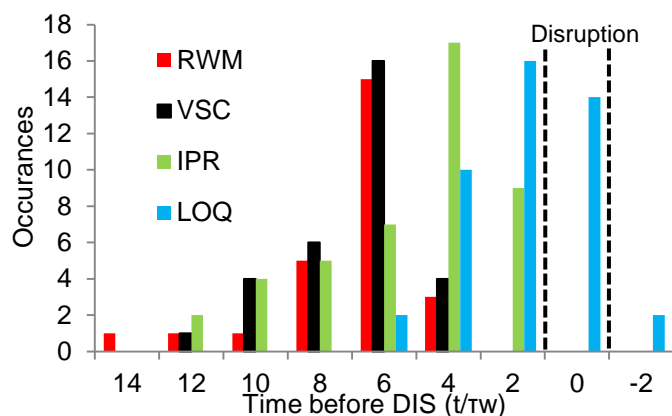
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