Characterization and forecasting of global and tearing mode stability for tokamak disruption avoidance*

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If the current in a tokamak is disrupted, a loss of plasma confinement results, which can lead to large heat deposition and forces on the surrounding structures. These disruptions have varying causes, and must be avoided for the safe operation of future fusion devices. It is important to identify disruption event chains and the specific physics elements which comprise those chains. Then if the events in the disruption chains can be forecast, cues can be provided to an avoidance system to attempt to break the chain. The new Disruption Event Characterization and Forecasting (DECAF) code [1] has the goal of characterizing and forecasting events that can lead to disruption of a tokamak plasma. The code is specifically meant to be portable, in that it was written to easily allow reading data from various machines without changes to source code, and modular, in that the pieces of code related to disruption events and physics models are separated into modules for ease of parallel development of code.

Examining common chains of events can provide insight into how to cue avoidance systems to return to normal plasma operations. One example is a resistive wall mode (RWM) detection algorithm which can be either a threshold test on magnetic signals or a more sophisticated kinetic RWM model. If the RWM can be detected in real-time by a growing exponential signal on an external magnetic sensor, it is also useful to know what the typical routes of plasma behavior directly follow the RWM so that plasma control systems may be employed to avoid them. In order to test the code's robustness and gain physics insight, DECAF analysis was performed on a database of 45 discharges from the National Spherical Torus Experiment (NSTX) that were pre-determined to have unstable RWMs which lead to disruptions. With the RWM $B_p^{n=1}$ lower sensor amplitude threshold of 30G ($\delta B/B_0$ ~ 0.67%) used here the RWM warning was typically found near the disruption limit. In 58% of the cases, the RWM event occurred

Event chain	Percent
RWM → VSC → PRP	30.8%
RWM → VSC → WPC	19.2%
RWM → PRP → VSC	11.5%
RWM → WPC → VSC	7.7%
RWM → IPR → WPC	7.7%

Table 1: *The five most common two-event combinations (partial event chains) that directly followed an RWM event in the 26 NSTX discharges where RWM occurred within 100ms of DIS.*

within 20 τ_w of the time of disruption (DIS) (where τ_w is the time scale of penetration of magnetic flux through the conducting structure, taken here to be 5 ms). Additionally, many of the earlier RWM warnings could not be considered false positives; they cause significant thermal collapses or "minor disruptions", with subsequent recovery. Of the 26 RWMs occurring within 100ms of the disruption, they were followed immediately by VSC (vertical stability control) 15 times. Further, looking at the two-event chains that happened directly after this set of RWMs, we find that even though there are theoretically 56 two-event combinations that could occur from the eight currently tested for (excluding RWM itself), just two two-event chains accounted for 50% of the cases and five accounted for 77%. These are shown in table 1, where PRP is excessive pressure peaking, WPC is wall proximity control, and IPR is plasma current not meeting request. Additionally, because these events are all happening in close conjunction with each other, and the time resolution of the diagnostic acquisition and analysis that defines the underlying variables differs, the timing in common chains sometimes flips, as can be seen from the first and third, and second and fourth entries in the table.

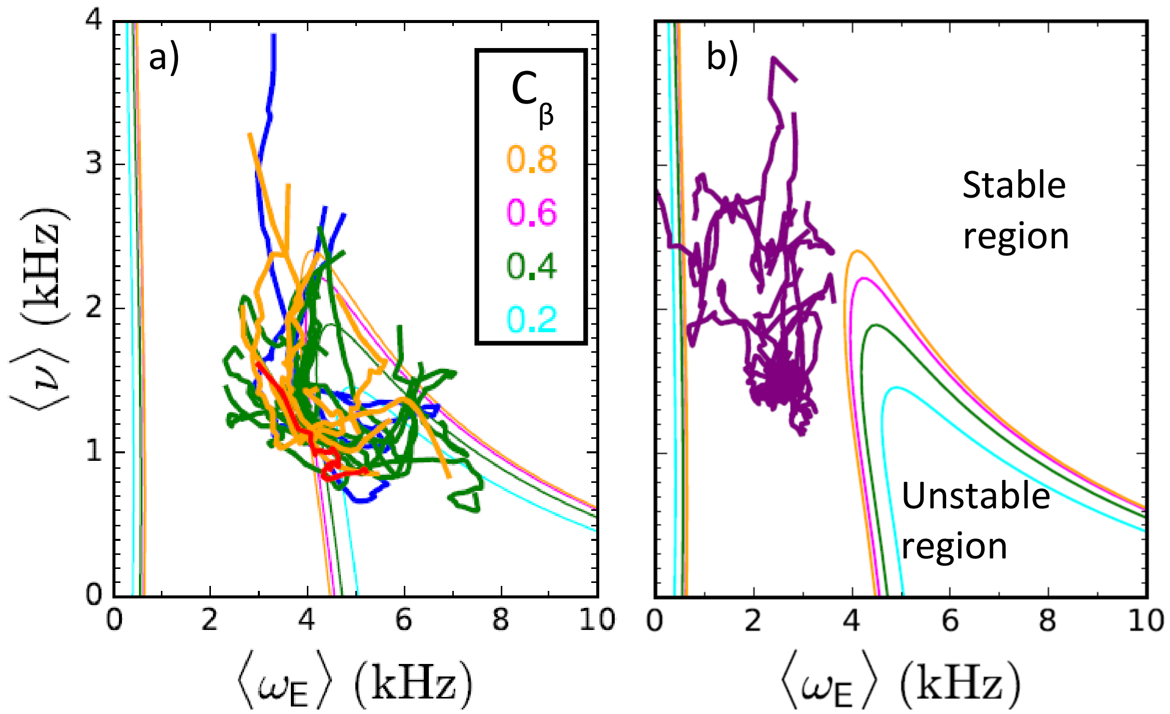

Figure 1: *Stability maps in ExB frequency, collisionality space for a) RWM unstable, and b) stable NSTX discharges, showing the DECAF kinetic RWM reduced model calculated trajectories of many discharges. The experimentally unstable discharges are generally calculated to enter the unstable region (shown for various values of* $C_\beta = (\beta_N - \beta_N^{no\text{-}wall})/(\beta_N^{with\text{-}wall} - \beta_N^{no\text{-}wall})$*), while the stable discharges generally do not.*

Recently, analysis with the MISK code has shown the importance of kinetic effects, such as resonances between plasma rotation and bounce and precession particle motions, on RWM stability [2]. This physics, as well as the effects of collisions, has now been incorporated in a "reduced" kinetic model in DECAF, streamlined for fast computation [1]. The goal is to forecast mode growth rate in real-time using parameterized reduced models to determine the change in potential energy δW terms that appear in the RWM dispersion relation. The model also incorporates expressions for the ideal no-wall and with-wall beta limits which are in good agreement with a large number of DCON code calculations [1,3], as well as δW_K - the change in potential energy due to kinetic effects. Gaussian functions, with parameters reflecting the experience of NSTX, are defined for δW_K as functions of ExB frequency and collisionality. The reduced model was tested on the same database of RWM unstable discharges from NSTX discussed above, as well as a set of stable discharges. Experimentally stable and unstable discharges were separated noticeably on a stability map in ExB frequency, collisionality space (see Fig. 1). The reduced model performed well in its first iteration on NSTX data, finding instability 84% of the time for experimentally unstable cases, and stability in 77% of experimentally stable cases [1].

The identification of rotating magnetohydrodynamic (MHD) activity, such as neoclassical tearing modes, is essential for tokamak disruption avoidance, given the ubiquity of such activity in many devices. A key cause of disruptions is the physical event chain that comprises the appearance of rotating MHD modes, their slowing by resonant field drag mechanisms, and their subsequent locking. Therefore a module was written for DECAF which both identifies the existence of rotating MHD modes and tracks certain characteristics that can lead to disruption. Characteristics such as identification of a mode locking time based on a loss of torque balance and bifurcation of the mode rotation frequency are examined to determine the reliability of such events in predicting disruptions. A goal is to detect such behavior as early as possible during a plasma discharge, and to further examine potential ways to forecast it. When completed, the resulting algorithms will be fully integrated into DECAF to declare the locked tearing mode (LTM) event. This capability could be used to provide a warning to use active mode control as a disruption avoidance mechanism, or to trigger a controlled plasma shutdown if desired.

This module has been tested with NSTX and NSTX-U data [4]. Many discharges with rotating MHD activity from NSTX and NSTX-U were examined. In the NSTX case an MHD stable period from 0.4-0.6s is visible due to high elongation ($\kappa \sim 2.7$) and lithium wall conditioning, but eventually rotating n=1 and n=2 activity return and the frequency spins down toward the end of the discharge. In NSTX-U rotating MHD is so far more common due to lower elongation ($\kappa \sim 2.3$) and no lithium wall conditioning.

The approach of the DECAF rotating MHD analysis module was to determine the mode peak frequency within a certain time interval by applying fast Fourier transform (FFT) analysis, and to see the bandwidth evolution. Although there are potential issues with handling multiple frequency peaks and currently the algorithm only distinguishes between odd and even n numbers (n number discrimination is now being added), the characterization algorithm already

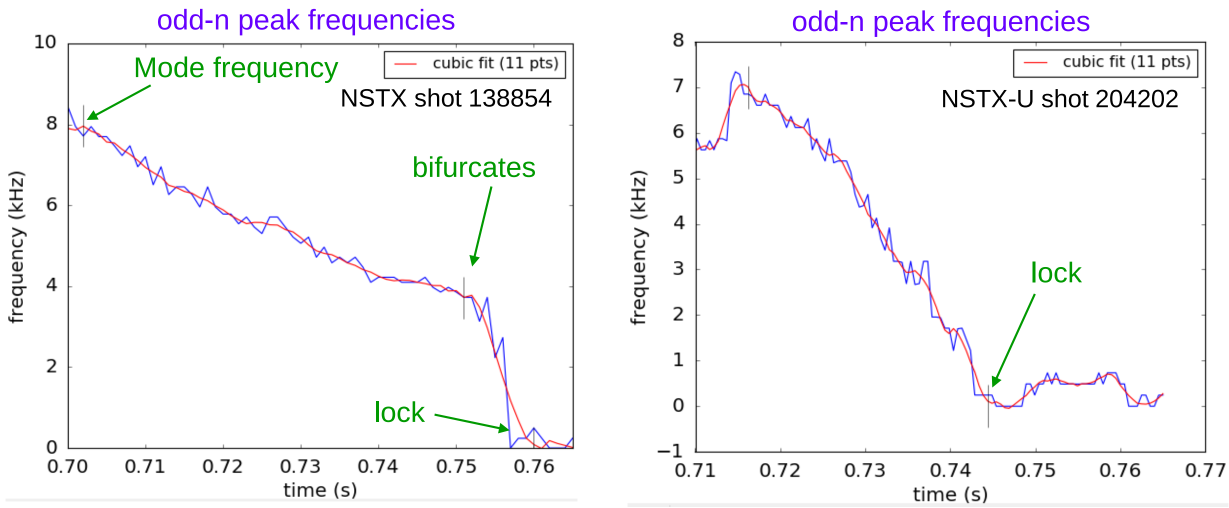

Figure 2: *DECAF characterization of odd-n frequencies for NSTX discharge 138854 (left) and NSTX-U discharge 204202 (right).*

shows that the expected bifurcation and locking events can be found. The algorithm looks for a "quasi-steady state" period, a potential bifurcation, and a possible mode locking. Figure 2 shows the analysis for odd-n frequencies for two example discharges. In the NSTX case the bifurcation point and lock were both found, while the code can also distinguish a locking that is not preceded by a bifurcation, as shown in the NSTX-U case.

Additionally, a simple physics model for mode rotation evolution and lock forecasting has been derived which allows island drag for both the "slip" and "no slip" conditions based on Ref. [5]. In this model if Ω_0 defines the steady state rotation, then a simple level of $\Omega_0/2$ defines the bifurcation point. This physics-based algorithm will be tested in DECAF in the future.

Next steps to the development and usage of DECAF include: continued improvement of accuracy of event determination, significant expansion of the type of events examined, the addition of intelligence to couple events, and the expansion of the dataset to multiple devices (e.g. DIII-D, KSTAR).

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