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Equilibrium and stability calculations of MAST spherical torus plasmas in preparation for MAST-U*

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Disruption prediction and avoidance is necessary in future MAST-U spherical tokamak discharges to enable long-pulse plasma operation. A framework has emerged which provides a comprehensive approach to disruption prevention through forecasting and avoidance, or prediction and mitigation of the detrimental consequences. In the present work, we use the Disruption Event Characterization and Forecasting (DECAF) code which utilizes this comprehensive framework. This approach provides a flexible framework to evaluate the proximity of plasma states to detected disruption events by coupled physics analyses, model criteria, and machine learning techniques. Stability modules in DECAF include evaluation of the no-wall beta limit, kinetic resistive wall mode stability, and rotating mode bifurcation into locked modes. In preparation for MAST-U these techniques are here applied to the MAST and NSTX spherical tokamak databases. Finally, accurate equilibrium reconstruction is crucial for the operation of MAST-U, as well as for stability analyses and disruption event characterization and forecasting. Progress towards producing kinetic equilibrium reconstructions for the MAST database, and setting up for MAST-U operations, is ongoing.

A reduced kinetic model for resistive wall mode stability based upon theoretical understanding has already been included in DECAF [1]. The dispersion relation is $(\gamma - i\omega_r)\tau_w = -(\delta W_{no\text{-}wall} + \delta W_K)/(\delta W_{with\text{-}wall} + \delta W_K)$, where ω_r is the real frequency of the mode, $\delta W_{no\text{-}wall}$ and $\delta W_{with\text{-}wall}$ are fluid, or ideal, changes in potential energy terms where the stabilizing device conducting structure is omitted or considered, respectively, and δW_K is the kinetic term. For the fluid terms, measurable quantities such as A, l_i (which is related to current profile peaking), β_N, and $p_0/\langle p \rangle$ are known to be influential on ideal MHD stability. The DCON stability code was developed to calculate the fluid δW terms and was previously used for thousands of calculations spanning the NSTX operating space [2]. Analysis of these thousands of calculations formed the basis of an analytical model for the fluid δW terms that was incorporated into the DECAF code

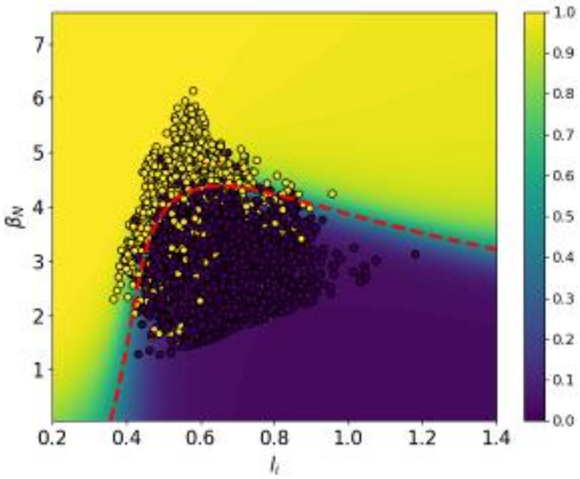

Figure 1: *β_N vs l_i decision boundary for the no-wall limit on the NSTX daatabase. The contour plot shows the probability distribution predicted by the neural network.*

[1]. The no-wall beta limit calculated for a MAST discharge using the NSTX formula already does a good job reproducing the measured limit. Improvements can be made for MAST-U analysis by analysing the MAST database with improved kinetic equilibrium reconstructions, and by using further improved beta limit calculations using machine learning.

Deep neural networks continue to show outstanding performance in classification tasks. Neural networks were proposed as a method for disruption prediction many years ago, and interest has recently grown rapidly. Here we use a neural network to classify the output of the ideal stability code DCON into stable and unstable regions, for a large database of equilibria from the NSTX tokamak. DCON provides the ideal change in plasma potential energy due to a perturbation of the confining magnetic field without the presence of a conducting wall, $-\delta W_{no\text{-}wall}$. $\delta W_{no\text{-}wall}$ changes from positive to negative when the plasma changes from ideal stable to unstable (the negative of the change in potential energy is used throughout the present paper so that, more intuitively, negative values are "below" the limit (stable) and positive quantities are "above" (unstable)). Stability regions can be evaluated by examining plots of $-\delta W_{no\text{-}wall}$ in the parameter space of normalized beta, β_N, versus internal inductance, l_i, pressure peaking, $p_0/\langle p\rangle$, or aspect ratio, A (see, for example, Fig. 1). Then neural network defined decision boundaries determine the marginal stability boundaries, increasing the accuracy compared to the previously defined no-wall limit modeling [2].

The overall no-wall beta limit can be determined by combining the defined boundaries with dependencies of $\beta_{N,no\text{-}wall}$ on the parameters used in the neural network. For determining the ideal, and ultimately kinetic mode growth rates, however, the *value* of $-\delta W_{no\text{-}wall}$, not just the sign, must be determined. To that end we have also developed another machine learning based approach to determine $-\delta W_{no\text{-}wall}$, adding more plasma parameters. We have tested with the random forest technique, which has also been recently employed in plasma physics research, specifically in disruption prediction [3]. The model also allowed us to extract features in order of importance, showing that the original β_N, A, l_i, and $p_0/\langle p\rangle$ are among the parameters that most affect the estimated values of $-\delta W_{no\text{-}wall}$, as expected by the underlying physics.

The no-wall and with-wall beta limits of projected MAST-U equilibria have also been studied, using the DCON and VALEN codes. A pressure scan of multiple equilibria analysed with both codes has indicated a no-wall limit just below 4. The VALEN model of the 3D conducting structure for MAST-U contains details of the vacuum vessel, coil cases, ports, and baffle structure. Including these structures, the with-wall ideal stability limit for these equilibria in MAST-U is projected to be between β_N of 5 and 6. Figure 2 shows the stability of the scanned projected MAST-U equilibria in the β_N vs. l_i parameter space. Work is ongoing to examine more projected equilibria.

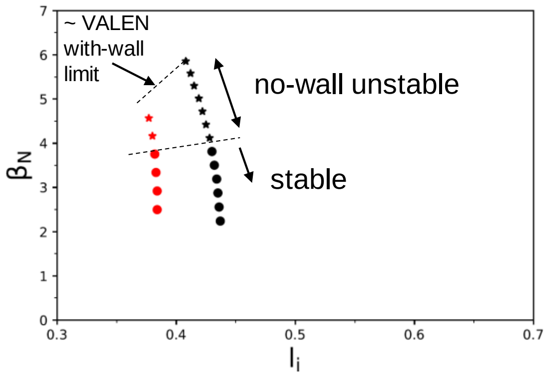

Figure 2: *Partial stability space of MAST-U projected equilibria as calculated by DCON and VALEN.*

The DECAF code consists of many separate physical event modules that provide warnings and declare occurrences of certain events leading to disruption and has been applied to the MAST database to examine density and vertical stability limits. Disruptivity diagrams indicate where disruptions occur in various parameter spaces, and examination of vertical displacement events show that they occur less often than in NSTX, but when they do occur it is in close time proximity to the disruption current quench. MAST operation was bound by the Greenwald density limit, and this limit was often reached in the current ramp-down which lowered the limit below the level of the experimental plasma density. An example disruptivity diagram for the MAST database in Fig. 3 shows that disruptions in MAST often occurred just above the Greenwald density limit.

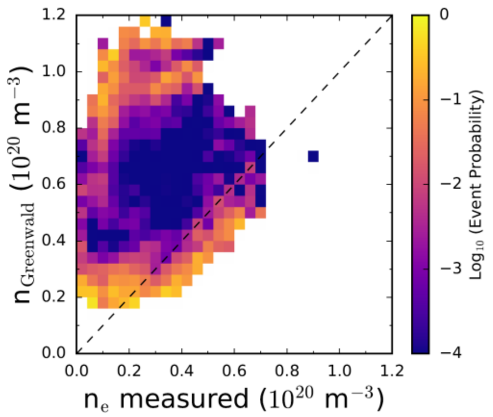

Figure 3: *Disruptivity diagram for the MAST database in the space of measured vs. Greenwald density. Contours indicate the probability of disruption occurring in the database of plasmas in each section of parameter space.*

Automated analysis of rotating MHD modes with tearing characteristics is available in DECAF with a module that produces physical event chains leading to disruptions through slowing of the modes by resonant field drag mechanisms and subsequent locking. An algorithm portable across tokamaks devices has been developed that processes the spectral decomposition and signal phase matching of magnetic probe signals for mode discrimination. Multiple modes occurring simultaneously are tracked and bifurcation of the toroidal rotation frequency and locking for each mode due to the loss of torque balance under resonant braking are detected. The information analysed for these modes along with plasma rotation profile and other plasma measurements can produce predictive warnings for the individual modes, along with a total MHD event warning signal showing initial success as a disruption forecaster. These capabilities were illustrated for NSTX in Ref. [4], where rotating MHD instabilities thought to be non-linearly saturated and slowly evolving resistive modes were found. The first step towards employing this analysis on the MAST database is to identify the toroidal magnetic probe signals and read them into DECAF analysis routines, reproducing MAST magnetic spectrograms. This has recently been accomplished for a series of MAST discharges using the outboard Mirnov array. Figure 4 shows a spectrogram produced by DECAF analysis. This work continues with spectrogram and mode number discrimination analysis for a large number of MAST discharges.

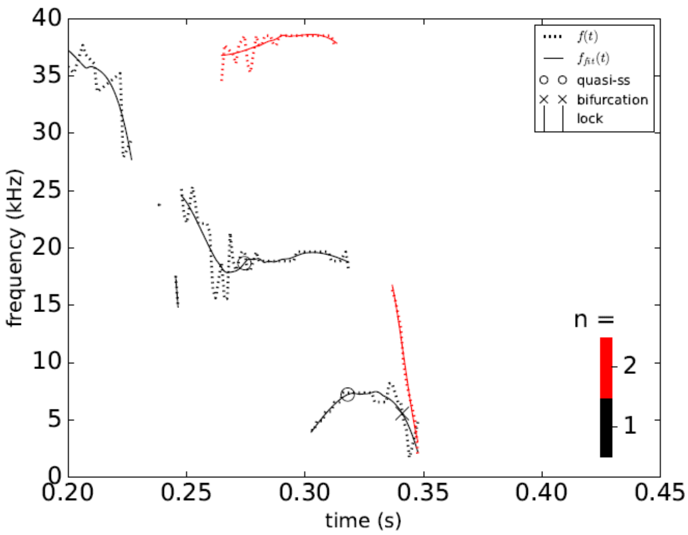

Figure 4: *Magnetic spectrogram of MAST discharge 23447 with DECAF automatically identified events indicated, for example a quasi-steady-state period of the low frequency 2/1 neoclassical tearing mode before a bifurcation of the frequency towards locking.*

The next stage of MAST and MAST-U stability analysis requires accurate kinetic equilibrium reconstructions. The analysis tools to create these reconstructions are now set up, including conducting structure models for both MAST and MAST-U, and automatic data retrieval of magnetic data and kinetic profiles. Magnetic test shots are being reconstructed to confirm consistency between the data and the model. Magnetics-only reconstructions to ensure validity, and then kinetic reconstructions including Thomson scattering profiles of electron density and temperature, charge exchange recombination spectroscopy profiles of ion temperature, and motional Stark effect measurements of magnetic pitch angle, will follow.

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