MULTI-DEVICE ROTATING MHD MODE LOCK AND DISRUPTION FORECASTER WITH REAL-TIME FEEDBACK FOR DISRUPTION AVOIDANCE

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The main goal of the fusion community is to achieve the construction and operation of a confinement device that can reliably generate a net surplus of practically generated energy from fusion reactions. Frequent events that challenge the successful, continuous operation of a tokamak device are major disruptions characterized by a current quench and typically preceded by a thermal quench. A critical aspect of large-scale advanced tokamak reactors is that the magnetic and thermal energy can be large enough to potentially damage plasma facing device components and reduce their lifetimes after enough major disruptions occur. Notably, the burning plasma fusion reactor currently under construction in France, ITER is expected to require a ceiling of 1% full performance shot disruptivity (possibly even lower if accounting for runaway electrons) [2]. In ideal conditions, tokamak plasmas form 2D parallel flux surfaces, each of a specific safety factor q. At rational q surfaces, finite resistivity allows for the reconnection of magnetic surfaces and the formation of island chains. Magnetic islands significantly increase transport across the width of the island flattening temperature profiles. First observed in TFTR, neoclassical tearing modes (NTM) are modes of island chains that are driven by helical reduction in bootstrap current and flattening of pressure profiles [3]. Formulated by Fitzpatrick [4] to develop tearing mode theory a torque balance model for the plasma can be used to understand mode dynamics as they lock to the wall reference frame. As a rotating MHD mode destabilizes and forms a non-axisymmetric magnetic island chain of saturated width in a poloidal flux surface it can affect the plasma rotation. As the magnetic eigenfunction of the mode interacts with the conducting structures that surround the plasma or a background non-axisymmetric error field it can create a dragging torque on the plasma up to, or even surpassing the driving beam torque and breaking the force balance. Ultimately, as resistive modes lock to the wall reference frame and start to overlap with other islands it can lead to electron temperature collapses near the rational surfaces which can then be followed by core crashes characteristic of minor and major disruptions. In addition to the electromagnetic force of the mode in the plasma near the island, there is also a fluid viscous drag that occurs from the perpendicular (to flux surfaces) viscous momentum diffusion. In total, we can define the inertial torque as the sum of these driving and dragging torque components:

$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_1}{\Omega} - \frac{(I\Omega)}{\tau_{2D}} \quad (1)$$

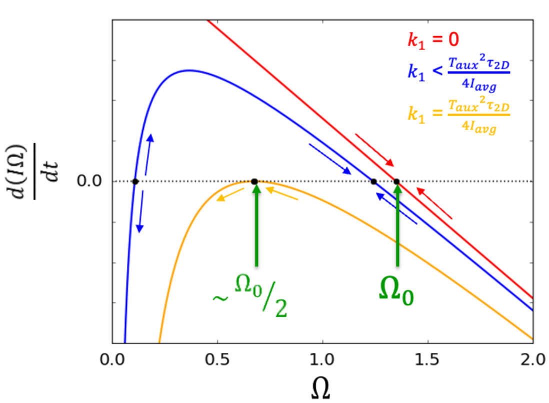

Fig. 1:Mode rotation frequency at bifurcation can be used as a threshold for forecasting mode locks

As part of the Disruption Event Characterization and Forecasting (DECAF) code [1], this torque balance formulation was used to develop a forecaster of the mode locking through a proximity calculation of this balance. A rotation threshold of this bifurcation point would determine the rotation frequency of the plasma below which the mode is expected to lock as shown in Figure 1.

$$\Omega_{\text{inf}} = \sqrt{\frac{k_1 \tau_{2D}}{I_{avg}}} \quad (2)$$

The forecaster was tested over the databases of multiple devices with ranges in aspect ratio, error field magnitudes, and operational parameters (KSTAR, NSTX-U, MAST-U, and DIII-D). In the previous KSTAR physics run a real-time version of the locked tearing mode forecaster was implemented with an algorithm that follows the diagram shown in Figure 2. The forecaster achieved complete accuracy in predicting the locked modes that led to disruptions in the nearly 50 experimental shots ran [5]. For the latest KSTAR physics run, some aspects of the algorithm were improved such as the low pass filtering of calculations and a PID controller was added to the algorithm that would actuate the current amplitude of a 3D n=1 rotating (50 Hz) applied field. The PID uses an error function based on the ratio of the mode rotation frequency to the bifurcation frequency activating the actuation past a threshold value and linearly ramping up the amplitude up to a maximum current of 4 kA/turn. Feedback actuation was successfully carried out. Comparing a shot that had a mode lock and disrupted with one where the applied field was actuated, though the disruption was not avoided in the latter, it did manage to prolong the time between the lock and disruption from tens of milliseconds to nearly half a second longer. Furthermore, the source of the disruption that followed is attributed to a vertical displacement event instead of a mode lock. Essentially, the previously seen mode lock induced disruption was avoided but whether the already deleterious presence of a nonlinearly saturated island width, the effect of the applied field, or the operational trajectory of the plasma without the mode lock was what led to the eventual vertical displacement disruption is unclear. These results motivate further experiments into this method of actuation and the coupling of multiple actuator strategies for multiple disruption precursor events like the vertical displacement.

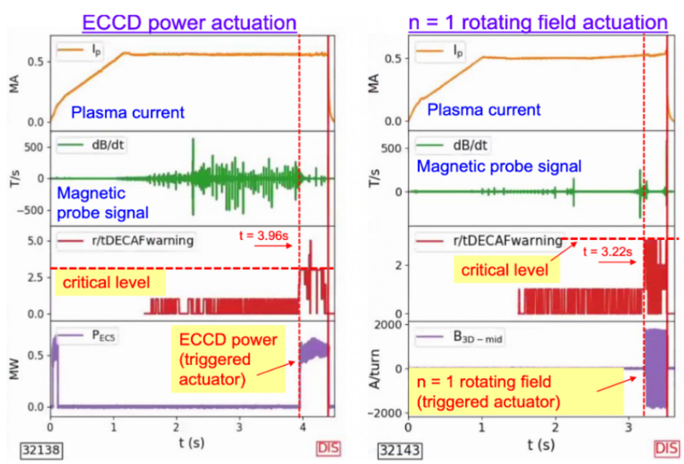

Fig. 2:Multiple actuation strategies were triggered in previous KSTAR run

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