Progress on Disruption Event Characterization and Forecasting in Tokamaks and Supporting Physics Analysis*

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Disruption prediction and avoidance is critical for ITER and reactor-scale tokamaks to maintain steady plasma operation and to avoid damage to device components. The present status and results from the disruption event characterization and forecasting (DECAF) research effort [1] are shown for multiple tokamak devices. The DECAF paradigm is primarily physics-based and aims to provide quantitative disruption prediction for disruption avoidance. DECAF aims to automatically determine the relation of events leading to disruption and quantify their appearance to characterize the most probable and deleterious event chains, and also to forecast their onset. The idea of disruption "event chains" largely follows from a manual analysis established by de Vries, et al. [2] for JET. DECAF aims to provide an understanding of the event dynamics leading to disruptions to ensure disruption forecasting extrapolability to ITER and future devices in which the production of disruptions in the device to teach non-physics-based approaches is highly restricted.

Present DECAF analysis of KSTAR, MAST, and NSTX databases shows low disruptivity paths to high beta operation. [1] Automated analysis of rotating MHD modes (Figure 1) now allows the identification of disruption event chains for several devices including coupling, bifurcation, locking, and potential triggering by other MHD activity. DECAF can now provide an early disruption forecast (on transport timescales) allowing the potential for disruption avoidance through profile control. Hardware to allow real-time evaluation of this activity on KSTAR is now being configured for installation in 2019. DECAF event characterization and event chain analysis shows that disruption forecasting analysis often starts during plasma states that can appear safe. This is illustrated using the disruptivity database plot shown in Figure 1. The regions of high disruptivity in the figure may be thought to be the most important based on human inspection. However, an apparent problem is that the region of high disruptivity at low normalized beta, β_N, and mid-range l_i as shown in the figure is not physically understood to be a dangerous operational region. The enigma is resolved by understanding that the plasma state can evolve significantly from more usual high performance parameters to the point at which the disruption occurs. This fact is completely missed, for example, by "disruption database" studies that only process data near the disruption time. In contrast, DECAF disruption event chain analysis of the discharge in

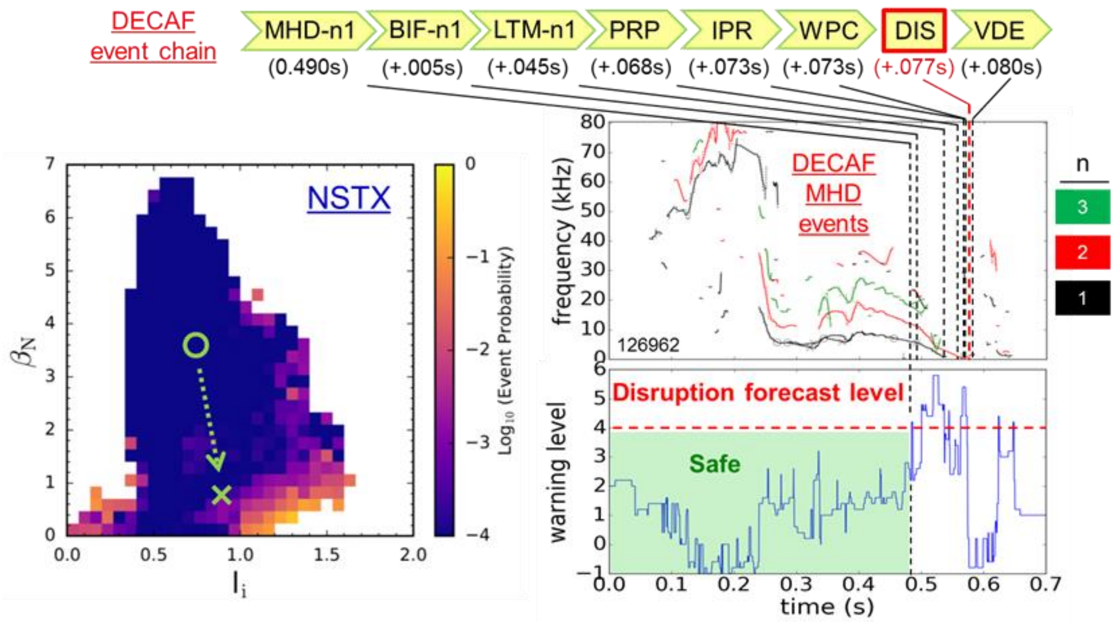

Figure 1: DECAF disruption event chain analysis and early disruption warning, showing that the event leading the chain occurred when (l_i, β_N) would indicate very low disruptivity.

Figure 1 that disrupts (DIS event in DECAF, marked by a green X in the figure) show that the *start* of the event chain appears in the region indicated by the green circle – which is *far* from what might be expected! The event chain in Figure 1 starts with a rotating n = 1 MHD mode (MHD-n1) that then bifurcates (BIF-n1) and subsequently locks (LTM-n1). The PRP event shows pressure peaking due to an H-L back-transition. The plasma can then no longer maintain the requested plasma current (IPR), comes too close to the wall (WPC) before DIS. After DIS, a vertical displacement event (VDE) is detected while the plasma current decays. The disruption warning level in the Figure shows that the disruption is forecast 77 ms before DIS - more than sufficient time to cue profile or control schemes for disruption avoidance.

Disruption prediction research using DECAF also allows *quantifiable* figures of merit (i.e. the plasma disruptivity) to provide an objective assessment of the relative performance of different models. This allows an assessment of how well the predictor performs compared to ITER needs. Figure 2 shows a progression of DECAF disruption forecasting models. The earliest models included about 10 events and were run on databases for which the events that led to the disruption were known and yielded very high performance (e.g. 100% true positives). A next evaluation of models focused on earlier forecasting once the first forecasting model was implemented in the code. True positives were found to be ~84%, which was a measure mainly of the single forecasting model. Forecasting models continue to be added to improve that performance. The most recent code testing has been on large databases ~ 10,000 shot*seconds of plasma run time tested (shown in Figure 1). This was done with a smaller number of events due to computer limitations. With 5 events, applied to all plasma shots from an NSTX database, DECAF shows performance levels of over 91% true positive disruption predictions. False positives in this analysis reached 8.7% which is fairly high. Code development that allows the events to poll each other will improve this.

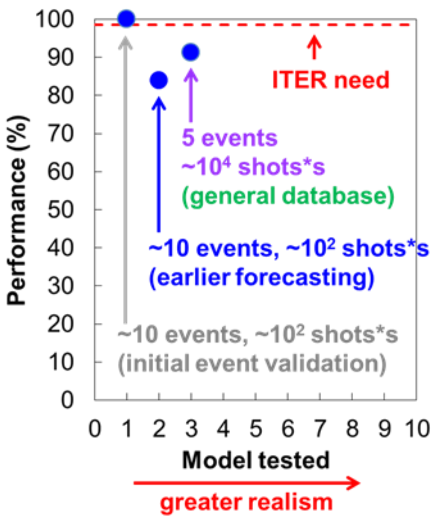

Figure 2: DECAF model performance evolution (true positive disruption forecast).

There is a significant physics analysis effort supporting DECAF model development too extensive to cover fully here (some addressed in other EPS 2019 presentations [3,4]). Two additional studies are summarized here. First, analysis of high performance KSTAR experiments using TRANSP shows that the non-inductive current fraction has reached 75%. Resistive stability including Δ' calculation by Resistive DCON is evaluated for these plasmas using kinetic equilibrium reconstructions with magnetic field pitch angle data to determine capability for instability forecasting. [4] To design experiments for the 2019 KSTAR run, predictive TRANSP analysis shows that with the new 2nd NBI system, (assuming usual energy confinement quality and Greenwald density fraction) 100 percent non-inductive plasmas scenarios are found with β_N = 3.5–5.0. These plasmas will provide a unique long pulse (~20s) database for disruption forecasting studies.

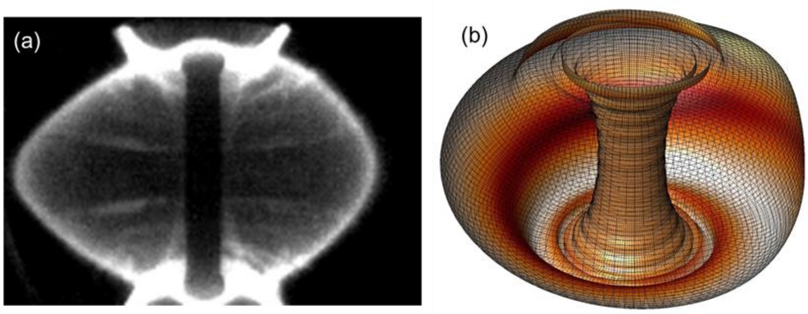

Figure 3: (a) fast camera image of MAST plasma (21436, t ~ 0.28s) displaying an RWM and (b) theoretically computed n = 1 RWM eigenfuction of unstable plasma 7090.

Second, new analysis of MAST has uncovered global MHD events at high β_N identified as resistive wall modes (RWMs) - slowly rotating, or locked. A stability analysis of MAST plasmas shows a significant ballooning shape of the theoretical three-dimensional RWM eigenfunction that compares well to fast camera images (Figure 3). The MAST RWM eigenfunction shape and growth rate appear significantly altered by the location of conducting structure compared to results from NSTX, which shows a much more spherical shape due to close-fitting copper plates. [5] The conducting wall stabilizing effect on the kink mode is computed to be relatively small in MAST. Figure 4(a) shows the RWM growth rate vs. mode drive for an RWM unstable MAST plasma with a no-wall β_N limit of 5.0 and a with-wall limit of 5.16. Another new result of this analysis shows that kink mode stabilization was primarily due to the vacuum vessel in MAST. In

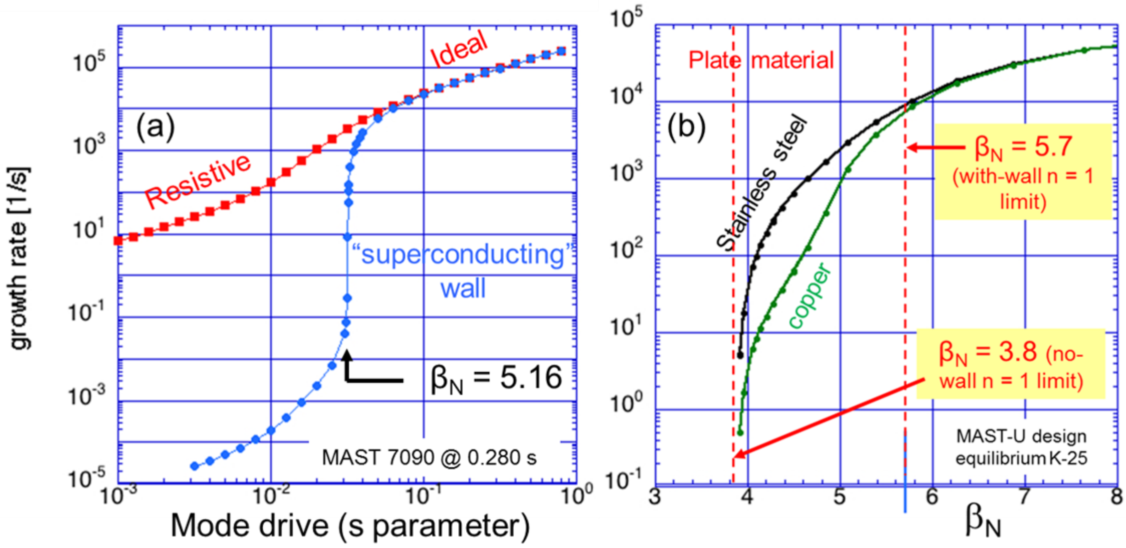

Figure 4: (a) MAST n = 1 RWM growth rate vs. mode drive with a no-wall β_N limit of 5.0 and a with-wall limit of 5.16 and (b) RWM growth rate for MAST-U design equilibrium with no-wall and with-wall limits of 3.8 and 5.7, respectively, showing a far greater kink stabilized range in β_N.

contrast, design equilibria of MAST-U plasmas show a significant increase in kink stabilization due to the addition of stainless steel divertor plates. The MAST-U analysis shown in Figure 4(b), including a 3D model of the conducting structure, shows an increased stabilized range of β_N from 3.8 – 5.7. MAST-U design equilibria with closer coupling between the plasma and the plates show further increases in the $n = 1$ with-wall β_N limit.

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