FIRST DEMONSTRATION OF DISRUPTION AVOIDANCE BY REAL-TIME PHYSICS-BASED DISRUPTION EVENT CHARACTERIZATION AND FORECASTING ON KSTAR*

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Disruption avoidance simultaneously addressing multiple off-normal events has been a decades long-sought capability for large, long-pulse auxiliary-heated tokamaks and a critical need for ITER and reactor-scale tokamaks to maintain steady plasma operation and to avoid damage to device components. Taking actions in real-time during tokamak operation to produce this elusive goal requires an understanding of the various underlying physical phenomena leading to the disruption. Physics-based disruption event characterization and forecasting (DECAF**) research [1] determines the relation of physical events leading to disruption. This research has produced event onset forecasts with high accuracy (100% accuracy in dedicated experiments exhibiting MHD-induced disruptions) and sufficiently early warning to allow disruption avoidance in ITER [2]. This high success has motivated very recent experiments that expand this capability to produce the first demonstration of disruption avoidance examining multiple events by this technique in the world-leading Korea Superconducting Tokamak Advanced Research (KSTAR) device. Multifaceted DECAF research also analyzes entire tokamak databases (presently 9 international databases accessible) the results of which formed the basis of these recent results.

The first real-time demonstration of disruption avoidance by DECAF was produced on KSTAR by connecting DECAF "Events" [1] to control actuators and applying "Event feedback". The number of Events is now significantly expanded (two in 2022) to eight, that examine various physical phenomena in their first real-time incarnation, including plasma current anomalies [3], vertical instability [4], an upgraded capability of predicting and forecasting MHD mode-locking [5], and impurity radiative collapses. A generalized real-time capability of measuring and understanding electron temperature collapses is also studied in these experiments, including analysis preparing for disruption avoidance in the near-term. The critical new multi-Event feedback capability leverages the high accuracy of DECAF Events [2] now cueing device actuators to produce disruption avoidance. Figure 1 shows a compilation of results using multiple Events illustrating examples of disruption prediction, avoidance, and optimization. The DECAF approach to disruption prediction is multi-tiered to ensure that sufficient time between the critical (Level 3) prediction warning and the disruption is sufficient for disruption mitigation in ITER (nominally 50 ms). If a DECAF Event does not meet this objective based on extensive multi-device database analysis, a DECAF "forecaster" Event is created based on appropriate physics models. As an example, the locked tearing mode Event (LTM) and LTM forecaster Event (LTM-f) that produced a 100% accuracy result in real-time on KSTAR were created for this purpose, with the LTM-f Event producing sufficiently early critical disruption warnings of between 0.7s – 1.5s [2,5]. In the disruption shown in Fig. 1, the plasma became vertically unstable and is accurately detected by the DECAF real-time vertical displacement Event (VDE). This Event was then used to monitor this plasma

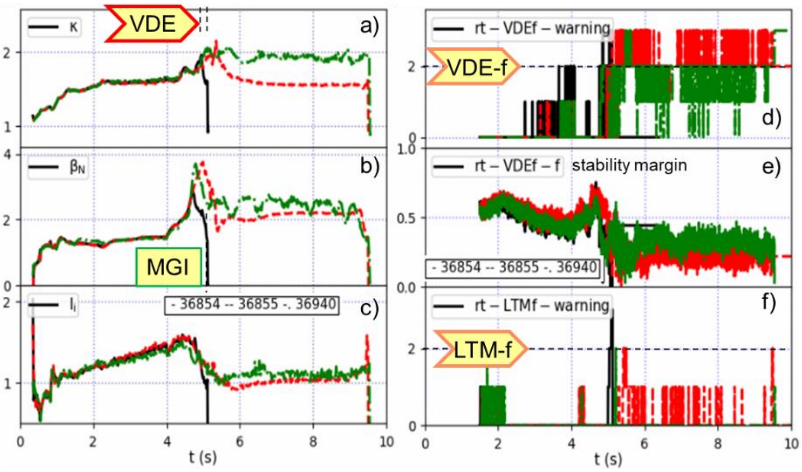

Figure 1: Disruption avoidance and optimization with DECAF VDE-f Event feedback using plasma shape control and LTM-f Event active; disruption mitigation triggers by VDE Event when feedback is disabled.

instability for subsequent plasmas and when predicted to produce a disruption, actuated the KSTAR massive gas injection system (MGI – Fig. 1a),b)). Supporting analysis used to create the VDE Event included testing the underlying model on data from thousands of plasmas in the KSTAR, MAST-U, and NSTX full device databases resulting in predictive accuracies of 100%, 100%, and 98.6% respectively with very low false positives, sufficiently stringent for ITER operation (Fig. 2). To produce an earlier disruption warning, a VDE forecaster Event (VDE-f) was created based on a vertical force balance model including the applied equilibrium field, 2-D plasma current, and eddy currents [4]. While this Event can be used for early disruption prediction in real-time, it is instead connected to an actuator that in combination produces the disruption avoidance shown in Fig. 1. DECAF Events reaching the "proximity warning" (Level 2) [1] can activate a variety of KSTAR control actuators including being input to the Proximity Control algorithm [6], and in this case were used to guide modifications to the plasma shape in real-time. The target plasmas produced high transient normalized beta, β_N up to 3.9 (record levels for KSTAR with tungsten divertor). Once VDE-f reaches the Level 2 warning (Fig. 1d), the real-time VDE-f Event stability calculation is compared to a target value of 1.3 to produce a target error for proportional gain feedback. The resultant Event feedback control signal is sent to the Proximity Control algorithm, which is configured to alter the plasma elongation for disruption avoidance (Fig. 1). The degree of change to the plasma shaping is determined by the Event feedback gain and gains in the Proximity Controller adjusted for these plasmas. Results of an initial optimization of the gain and controller settings is shown in Fig. 1. Due to the physics understanding and database analysis that DECAF Events provide, plasma experiments demonstrated the capability and provided physics understanding immediately following the activation of Event feedback components. In the initial case that avoids the disruption due to the high β_N transient, plasma elongation, κ, drops to 1.6 with a related drop in β_N to 2. Initial plasma optimization increased κ to 2, with β_N increased to 2.7 (Fig 1a),b)). In the past year, KSTAR was outfitted with tungsten first wall tiles below the plasma midplane. Carbon first wall tiles remain in the upper part of the device. While plasmas shown in Fig. 1 were upper single null, the disruption avoidance was successfully repeated in a lower single null configuration, with some variations made to actuator settings.

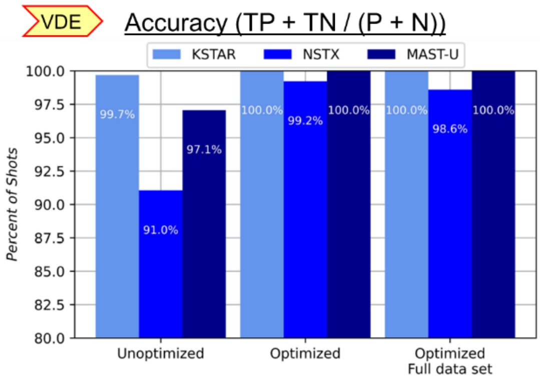

Figure 2: High accuracy disruption prediction by DECAF VDE Event in KSTAR, MAST-U, NSTX

New and updated DECAF Events were recently added with feedback capabilities including an LTM-f Event that now actuates an n = 1 rotating field to avoid mode locking. This Event feedback was active, but not triggered in Fig 1(f) as warnings were transiently at or below the proximity Level. ECH/ECCD used to alter the electron temperature profile and plasma internal inductance was also attempted in Event feedback by VDE-f. These new DECAF Events were run simultaneously, including VDE-f actuating both shaping control and ECH/ECCD, LTM-f actuating an n = 1 rotating field, and VDE disruption prediction set to trigger MGI for plasma shutdown. Other new Events have been studied using the tokamak databases and each have warning levels that correlate with plasma disruptions including a generalized capability to diagnose electron temperature collapses (TEC) that provide early disruption prediction by ~ 0.7s and good condition separation (Fig. 3). Also, a real-time impurity radiative collapse Event (IRC) just recently installed correlates with disruptions and will be used in feedback to actuate core ECH to avoid radiative collapse-induced disruptions. These disruption prediction database analyses will be shown, including how they influence real-time Event designs, along with experiments that tested the pre-programmed response of actuators cued by the Events.

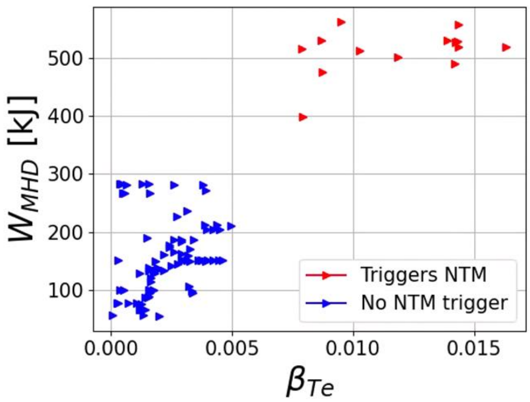

Figure 3: Separation of T_e collapses triggering NTM-induced disruptions for KSTAR TEC Event

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**U.S. and international patents pending

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