High Accuracy Physics-Based Tokamak Disruption Event Characterization and Forecasting with First Real-Time Application

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Disruption prediction and avoidance is critical to maintain steady plasma operation and to avoid damage to device components in ITER and reactor-scale tokamaks. Physics-based disruption event characterization and forecasting (DECAF) research determines the relation of events leading to disruption, and aims to provide event onset forecasts with high accuracy and sufficiently early warning to allow disruption avoidance [1]. The first real-time application of DECAF was made on the KSTAR superconducting tokamak including initial connection to control actuators. Dedicated plasma experiments focusing on disruptions caused by locking MHD instabilities produced over 50 plasma shots with nearly equal disrupted / non-disrupted cases that were forecast with 100% accuracy. An MHD mode locking forecaster, using a torque balance model of the rotating mode, was implemented and utilized in real-time to produce these results. This forecaster was also used several times in these experiments to cue controlled plasma shutdown, trigger disruption mitigation using the KSTAR massive gas injection (MGI) system, and actuate electron cyclotron current drive and n = 1 rotating 3D fields for future disruption avoidance. DECAF warning triggers were issued well before the expected plasma disruption time and early warning guidance timing given by ITER disruption mitigation needs. Significant hardware and software for real-time diagnostic acquisition and DECAF analysis continue to be installed on KSTAR. Real-time magnetics, electron temperature, T_e, profiles from electron cyclotron emission (ECE), 2D T_e fluctuation data from ECE imaging, and toroidal velocity profiles show excellent agreement with offline data/analysis. High bandwidth T_e profile measurements are used to reconstruct a 'crash profile' to computationally identify sawteeth, ELMs, and other MHD as NTM triggers and as direct disruption precursors. Different disruption event chains are observed based on the plasma state at the time of the trigger event. Offline analysis has access to data from an expanding list of tokamaks including KSTAR, MAST-U, MAST, NSTX-U, NSTX, DIII-D, ASDEX-U, and ST-40 to best understand, validate, and extrapolate models. Fully automated analysis shows for datasets spanning entire run campaigns very high true positive rates, in some cases over 99% with early forecasting. A multi-device study conducted for plasma vertical instability produced objectively high accuracy levels for real-time capable modelling with prediction accuracy of 91.0% - 99.7% before warning threshold optimization. With threshold optimization, prediction accuracy reaches 98.6% - 100% over multiple devices.
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References

[1] S.A. Sabbagh, et al., *Phys. Plasmas* **30**, 032506 (2023); https://doi.org/10.1063/5.0133825