Critical Need for Disruption Prediction, Avoidance, and Mitigation in Tokamaks

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The near-complete elimination of damaging plasma disruptions in fusion-producing tokamaks, including ITER and FNSF, is the present “grand challenge” in tokamak stability research. Meeting this significant goal will require multiple approaches, use various physics and engineering disciplines, and is best approached by a national research effort. Experiment and theory will need to work in concert to reach this goal. As the plasma evolves, including dynamics caused by transient phenomena or changes in operational state (e.g. confinement transitions, formation of localized internal barriers, dominant alpha heating), stability should be predicted theoretically and measured experimentally. As the plasma evolves toward less stable states, actuators can be used to change plasma characteristics and avoid instability consistent with high fusion power output. When profile control does not avoid instability growth, active mode control systems can be used to maintain safe levels of mode amplitude as the plasma is evolved back toward a stable state. When a disruption is unavoidable, mitigation systems can be triggered to shut down the plasma without causing excessive device damage. A 10 year national research effort to solve the disruption problem in tokamaks (both large thermal collapses and current quenches) will address:

(1) Prediction / detection: Real-time physics-based evaluation of stability criteria can be expanded by greater understanding, as well as exploitation of improving parallel computation technology (e.g. ideal MHD analysis such as DCON). Simplified evaluation of complex models, such as kinetic MHD, will allow greater capability in determining marginal stability conditions for equilibrium profiles (e.g. safety factor, pressure, plasma rotation) through dedicated experiments and model validation. Further developments range from non-linear MHD codes with synthetic diagnostics to large data-driven statistical predictions. Advanced real-time detection using physics models of global instability response (e.g. from resistive wall modes) has been built into state-space control models and needs continued development. MHD spectroscopy of applied 3D tracer field to measure global mode stability must be proved effective in real-time use. Non-magnetic mode detection diagnostics are desirable and should be applied routinely. Developments in these areas will further improve input to tokamak disruption warning system algorithms.

(2) Avoidance: Advanced control algorithms are successfully being implemented but need significant further development. Control of equilibrium profiles remains a generally untapped opportunity to avoid unstable conditions. Neutral beam injection, 3D fields, and core fueling techniques are some examples of actuators. Off-normal event response algorithms need to intelligently prioritize multiple actuators. The large range of physics models and MHD spectroscopy used in real-time for detection also provide real-time guidance on stability gradients in operational space, and can be used to steer away from instability. If predictors indicate that instability is unavoidable, a controlled shut down should be initiated. Theoretical plasma simulators can be developed to test these algorithms to make faster progress. Active mode control techniques can be used once mode onset is detected and transport-timescale avoidance techniques are too slow. Physics-based real-time algorithms, sensors, and actuators have shown significant successes for RWM and TM control. These systems must be generalized to further improve performance and be proven to work over long-pulse. Evolution toward non-magnetic elements in these systems is also important.

(3) Mitigation: In the small percentage of shots where disruption cannot be avoided, a fast discharge termination method is needed to minimize damaging effects including large heat loads from thermal quenches, asymmetric halo currents, and runaway electrons. Further progress using massive gas injection (MGI) is required, including aspects and understanding of gas penetration efficiency (e.g dependence on poloidal location, including the X-point region) and spatial distribution of heat and radiation loads, with related theoretical modeling. Shattered pellet injection (SPI) should be further developed if MGI proves inadequate. New ideas include fast impurity injection by electromagnetic means, and sacrificial limiters, perhaps using low-Z liquid metals. All techniques should allow rapid recovery of high plasma performance after use. Control of the decaying plasma and runaway electron population needs further development to produce a controlled shutdown. Halo current diagnosis in present devices needs to be significantly improved to measure and understand the dynamics, toroidal asymmetries, and related forces.