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Control Physics Advances in DIII-D and Long Pulse Devices Applied to Robust, Disruption-Free Operation

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The field of plasma control has assumed a key role in the era of approaching fusion reactor experiments including ITER and CFETR. The demands of such devices to operate robustly and disruption-free require levels of reliability and performance only possible with control algorithms based on sufficiently accurate models. DIII-D has contributed significantly to the worldwide advancement of control physics (the development of physics understanding and models specifically needed for control design), and to the use of control methods to enable and maximize the effectiveness of experimental studies. Through collaborations based on using the common framework of the DIII-D Plasma Control System (PCS) and control modeling tools such as the GA Tokamak System Toolbox (TokSys), control research has advanced dramatically in the last decade at DIII-D, NSTX, EAST, KSTAR, and other devices. Recent control advances at these devices, as well as applications to the ITER design, illustrate the importance of physics understanding to inform model-based design for high control reliability and performance, as well as the importance of excellent control to elucidate physics understanding in unique ways.

High performance control of the safety factor profile in DIII-D has been accomplished through design based on sophisticated dynamic models, with a variety of control algorithm synthesis approaches. The resulting capability to attain a desired target early in a discharge and sustain the profile with high accuracy enables more precise study of the plasma stability and transport characteristics. Maintenance of profiles in a state sufficiently far from stability or controllability boundaries holds the further promise of ensuring robust disruption-free operation. Regulation of divertor detachment in DIII-D using model-based control algorithms has enabled precise scans that illuminate physics processes that would otherwise be difficult to observe. The detailed response of the near-target plasma temperature to neutral injection in the detachment process has been mapped using this unique control capability. Discharge control validation is a critical requirement for ITER, for which the control scenario of each discharge must be confirmed in simulation to satisfy machine limits and provide high probability of robust disruption-free execution. This capability has been demonstrated in routine use by connecting the DIII-D Plasma Control System (PCS) to simulations including axisymmetric resistive 2D plasma evolution and relevant plant system elements. In order to enable more precise study of fully non-inductive scenarios, an algorithm that explicitly regulates the loop voltage to zero was developed and applied in EAST. Discharges using the algorithm were able to maintain zero average ohmic current drive, an essential capability for analysis of the resulting steady state profiles. A new algorithm for real-time calculation and specification of target feedforward coil current trajectories in KSTAR enables improved accuracy in adjusting for variations in plasma resistivity in the plasma current and shape control. Model-based continuous control for regulating proximity to vertical controllability boundaries and preventing vertical displacement event disruptions through effective exception handling algorithms have been developed and applied to ITER scenarios.

These and other advances in tokamak control serve to illustrate the substantial reliance of control success on physics understanding, and equally the reliance of physics progress on high performance control. With sustained attention to both aspects of this process, experimental programs in present day and next-generation devices will continue to benefit from exploiting this powerful synergy.

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