MHD and Plasma Control in ITER

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Controlling the plasma in ITER to achieve its primary mission goals of Q=10 (Q=(fusion power output)/(input power)) for 300 – 500 s and quasi-steady-state operation with Q=5 for ~3000 s requires a complex and sophisticated plasma control system (PCS) based on understanding and extrapolating physical phenomena present in existing tokamaks. An overview of the physical phenomena on which the ITER PCS will be based is presented in this paper with particular emphasis on the magnetohydrodynamic (MHD) instabilities that are expected in ITER. The ITER PCS will control 1) wall conditioning and tritium removal, 2) plasma axisymmetric magnetic control, including plasma initiation, inductive plasma current, position, and shape control, 3) plasma kinetic control, including fuelling, power and particle flux to the first wall and divertor, non-inductive plasma current, plasma pressure and fusion burn control, 4) non-axisymmetric control, which includes sawteeth, neoclassical tearing modes (NTMs), edge localized modes (ELMs), error fields and resistive wall modes (RWMs), and Alfven eigenmodes, and 5) event handling, including changing the control algorithm or scenario when a plant system fault or a plasma related event occurs that could affect plasma operation, which includes disruption mitigation. The ITER PCS relies on ~50 diagnostic systems to assess real-time plasma conditions and a number of fueling (pellet and gas injection), heating and current drive (neutral beam injection and ion and electron cyclotron), and magnetic field actuators (central solenoid (CS), poloidal field (PF), in-vessel vertical stability and ELM coils, and external correction coils) to act on the plasma to carry out its control functions.

At high plasma performance, the control of MHD instabilities will become particularly important in ITER not only to maintain the fusion burn, but also to avoid potential damage to the first wall. Sawtooth destabilization with electron cyclotron current drive (ECCD) and ion cyclotron range of frequency (ICRF) heating is required to keep the sawtooth frequency high and amplitude low to reduce seed islands that lead to NTMs. At high β = (kinetic pressure)/(magnetic pressure), such seed islands can grow rapidly to a significant fraction of the minor radius to substantially degrade energy confinement or lead to disruptions. Localized ECCD will be used to reduce and control the size of NTMs. Resonant magnetic perturbations produced by three sets of 9 in-vessel ELM coils mounted to the upper, lower, and outboard midplane wall will be used to stabilize ELMs. Pellet injection into the plasma edge at 30 – 50 Hz is also envisioned to increase the ELM frequency to reduce the amplitude of ELM perturbations on the divertor. Three sets of 6 external correction coils on top, bottom, and at the outboard midplane of ITER will be used to control error fields. Reduction of error fields together with resonant magnetic perturbations produced by the in-vessel ELM coils will be used to control RWMs at high β. Experimental and theoretical results indicate that the stability of Alfvén eigenmodes is sensitive to changes in the density and safety factor (q) profiles, and to changes in the edge through plasma shaping. The event handling system must include algorithms to predict, avoid, and mitigate disruptions, where the plasma thermal energy and current are suddenly lost and the plasma impacts the first wall or divertor. When a disruption cannot be avoided, the PCS will ask the Central Interlock System (CIS) to trigger the disruption mitigation system (DMS). This DMS will quickly (~20 ms) inject a massive amount of material (e.g., neon + deuterium) either with pellets or high pressure gas to quickly radiate away the plasma energy, distribute the heat load, and reduce halo currents in the current quench to reduce the $\mathbf{j} \times \mathbf{B}$ forces on the vessel. A separate system may also be required to mitigate runaway electrons generated in the disruption to avoid localized damage to the first wall.