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Divertor-safe Nonlinear Burn Control in Long-Pulse Reactor Operation

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The control of the core-plasma kinetic state determining the overall fusion power, usually referred to as burn control, arises as one of the most fundamental problems in nuclear fusion. Feedback control of the burn condition will be necessary to avoid undesirable transient performance, to respond to changes in plasma confinement, impurity content, or operation conditions, which could significantly alter the plasma burn, and to avoid potentially disruptive plasma conditions due to thermal instabilities. In order to keep the operating point far from stability, controllability and safety boundaries, and therefore avoid disruptions and protect the device while regulating the fusion power, a well-design burn controller should be able not only to achieve tight regulation around a desired operating point by rejecting perturbations in temperature and density but also to drive the plasma from one operating point to another during the burning-plasma phase, to access to and exit from the burning-plasma phase, to incorporate operational constraints arising from temperature and flux limits imposed by the plasma facing components, and to handle the nonlinear coupling with other competing controllers using shared actuators.

These control objectives demand not to neglect the nonlinear dynamics of the plasma during the control synthesis process. In order to overcome the operability limits imposed by the linearization of the burn dynamics, nonlinear techniques for burn control have been proposed to account for the non-local character of the dynamics. Control designs incorporating the nonlinear dynamics of the plasma have shown higher levels of performance, stability, and robustness against model uncertainties. These controllers utilize several actuators simultaneously, using auxiliary power modulation to prevent quenching, impurity injection (increase of radiation losses), confinement degradation (reduction of plasma energy) and isotopic fuel tailoring (decrease of fusion power density) to cool down the plasma and stop thermal excursions, and fueling modulation to regulate the density. Since the primary goal of a burn controller is usually to regulate volume-averaged properties of the plasma (e.g., fusion power or Q), zero-dimensional models are appropriate for control synthesis. However, if the goals were different for different regions of the plasma (e.g., core vs. edge), dynamic models capturing the spatial dependence would be needed for control synthesis. In any case, control testing in one-dimensional simulations would be critical before implementation.

A burn-control solution with the capabilities described above will demand not only the design of nonlinear robust/adaptive control algorithms but other key components such as: i- state observers to estimate in real time from limited-in-number and noisy diagnostics the plasma properties needed for control; ii- online optimizers to determine in real time the references needed by the controller given the desired operating point and the constraints imposed by the core-edge dynamics; iii actuator allocation algorithms to map in real time the heating and fueling requests by the controller to the available actuators while taking into account actuator dynamics and time-varying model uncertainties in the mapping. An overview of the state of the art and open challenges in burn control for long-pulse reactor operation will be provided.

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