Integrated Plasma Control for High-Performance Tokamaks[*] FT

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Sustaining high performance in a tokamak requires controlling many equilibrium shape and profile characteristics simultaneously with high accuracy and reliability, while suppressing a variety of MHD instabilities. Integrated plasma control, the process of designing high-performance tokamak controllers based on validated system response models and confirming their performance in detailed simulations, provides a systematic method for achieving and ensuring high control performance. For present-day devices, this approach can greatly reduce the need for machine time traditionally dedicated to control optimization, and can allow determination of high-reliability controllers prior to ever producing the target equilibrium experimentally. A full set of tools needed for this approach has recently been completed and applied to DIII-D and NSTX. This approach has proven essential in the design of several next-generation devices including KSTAR, JT-60SC, and ITER. We describe the method, results of design and simulation tool development, and recent research which has produced novel approaches to plasma shape and MHD control. This design method is illustrated in producing successful active feedback suppression of the neoclassical tearing mode (NTM) [1] in DIII-D, and in analyzing ITER gap control.

Figure 1 illustrates the integrated plasma control process schematically. Because the use of any individual actuator in a tokamak control system can strongly affect more than one physics element, the nature of those responses must be built into models used to design high performance controllers. To provide the necessary controller reliability, these highly coupled models must also be validated against experiments across a broad range of operating regimes. Multivariable design techniques provide a rich array of tools for designing high reliability, robust controllers based on validated models. Simulations are important for testing control performance in the presence of actuator saturation, power supply nonlinearities, and other complex system details, as well as to test performance in the presence of realistic nonlinear plasma responses, particularly when the plasma response diverges significantly from the linearized design model response. Two kinds of simulation are essential for confirmation of performance: "offline" testing of controllers implemented in a simulation, and "hardware-in-the-loop" testing of the controller implementation running on actual real-time computers communicating with the simulation. The latter capability allows verification of the correctness of the control implementation in the plasma control system (PCS) and the performance of the algorithm when running on actual real-time computers against a realistic system

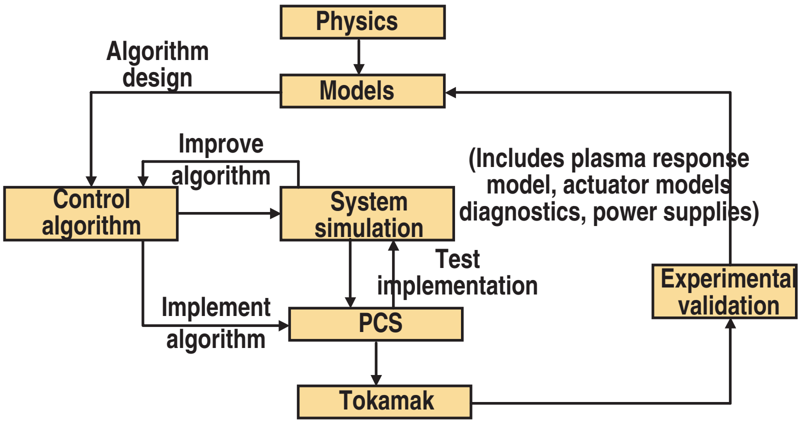

Fig. 1. Integrated plasma control process.

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response. These elements, now in operational use at DIII-D, comprise a unique and complete integrated plasma control tool set for design and commissioning of high reliability control.

Development of the NTM suppression control system for DIII-D provides an example of this integrated plasma control process applied to a non-axisymmetric MHD control problem. NTM islands can be suppressed by replacing the bootstrap current deficit with ECCD current driven at the island q-surface. In the absence of realtime q-surface reconstruction (only recently made available in the PCS), the degree of misalignment must be inferred from variations in fast magnetic measurements (reflecting island size) as the relative locations of island and ECCD are varied. A simplified version of the modified Rutherford equation (MRE) [1] was used to model the island response to ECCD, providing the first element needed for the integrated plasma control process. Alignment control algorithms were designed and their operating parameters were optimized using this model. Adequate performance robustness was confirmed with detailed simulations including the full MRE and representations of ECCD and PCS dynamics. Correct functioning of the control implementation was then confirmed using hardware-in-the-loop tests of the PCS computers. Figure 2 shows a comparison of the mode suppression model and experimental island suppression responses (top frame; full suppression achieved in 200 ms) to variation in the degree of alignment between island and ECCD location (2nd frame). Using integrated plasma control techniques, the system was designed with sufficient reliability to produce successful suppression the first time this algorithm was applied experimentally.

The integrated plasma control approach has also allowed development of novel high accuracy axisymmetric control algorithms for DIII-D in regimes where plasma boundary response and nonlinear constraints must be considered. Study of dynamic shape response has shown that the resistive response of edge currents play a significant role in boundary control in DIII-D. Demand for high accuracy shape controllers on DIII-D has thus led to development of new plasma models for control design that accurately represent the linear nonrigid resistive plasma response. While these new models have increased linear controller accuracy, study of fundamental control in tokamaks has revealed important limitations to linear control when operating near coil limits. The need for nonlinear current and voltage demand management near these limits has been quantitatively evaluated and solutions have been designed and implemented on DIII-D. These solutions are of even greater importance to devices such as ITER with highly constrained performance envelopes.

Figure 3 shows an example of the integrated plasma control approach applied to ITER design and analysis. A detailed axisymmetric simulation of the ITER system was developed, based on models extensively validated on DIII-D. An ITER PCS was then constructed based on software from the DIII-D PCS, and was run in closed loop with the ITER model in hardware-in-the-loop simulation mode to study realistic gap responses to an initial disturbance. This end-to-end process shows the power of the approach, and demonstrates the readiness of presently-available tools to address the control design and commissioning needs of ITER and other next-generation devices.

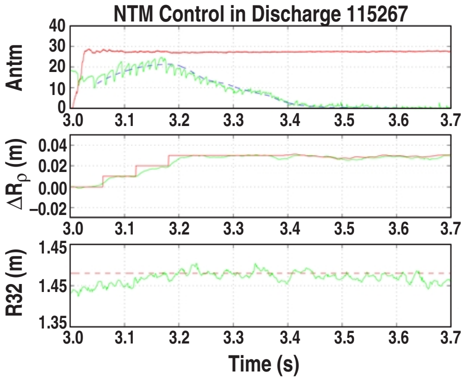

Fig. 2. NTM suppression.

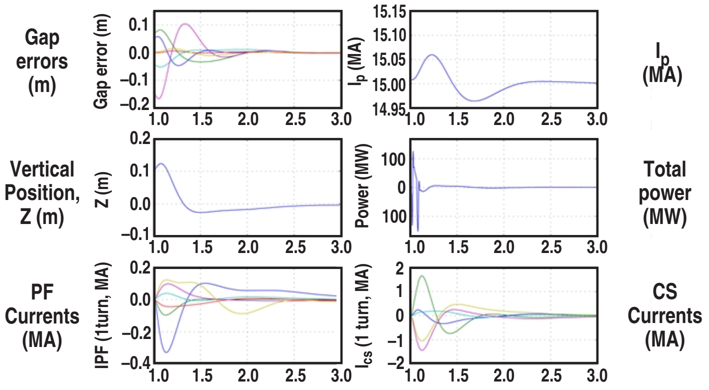

Fig. 3. ITER hardware-in-loop simulation.

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[1] R.J. La Haye, *et al.,* Phys. Plasmas **9**, 2051 (2002).