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## Development of ITER-Relevant Plasma Control Solutions at DIII-D\* FT

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The requirements of the DIII-D physics program have led to the development of many operational control results with direct relevance to ITER. These include new algorithms for robust and sustained stabilization of neoclassical tearing modes (NTM) with electron cyclotron current drive (ECCD), model-based controllers for stabilization of the resistive wall mode (RWM) in the presence of edge localized modes (ELMs), coupled linear-nonlinear algorithms to provide good dynamic axisymmetric control while avoiding coil current limits, and adaptation of the DIII-D plasma control system (PCS) to operate next-generation superconducting tokamaks. Development of integrated plasma control, a systematic approach to model-based design and controller verification, has enabled successful experimental application of high reliability control algorithms requiring a minimum of machine operations time for testing and tuning. The DIII-D PCS hardware and software and its versions adapted for other devices can be connected to integrated plasma control simulations to confirm control function prior to experimental use. This capability has been critical to control system implementation for tokamaks under construction.

NTM control in DIII-D has benefited from application of the integrated plasma control design approach, which has produced several search algorithms to find optimal  $q$ -surface/ECCD alignment, as well as active tracking algorithms to maintain alignment of the relevant resonant surface with the ECCD deposition spot after mode stabilization [1]. Experiments in the last 2 years have demonstrated robust and sustained suppression of the 3/2 and 2/1 NTM (separately) using these algorithms. Active tracking is now accomplished with realtime reconstruction of resonant  $q$ -surface geometry using motional Stark effect (MSE) measurements. Figure 1 shows results of an experiment

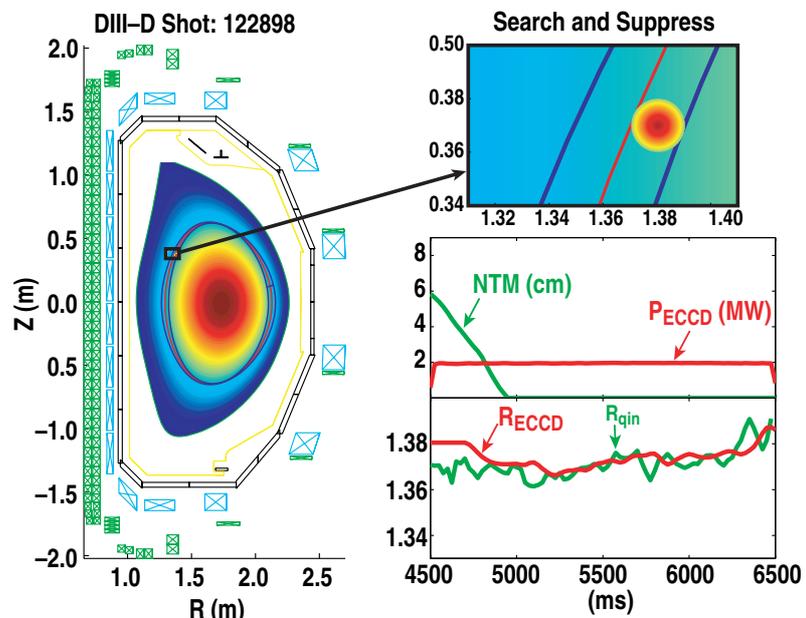


Fig. 1. Suppression of  $m/n=2/1$  NTM through systematic search (before suppression) and active tracking (after suppression).

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illustrating use of a systematic search algorithm followed by active tracking with realtime  $q$ -profile reconstruction. The active tracking algorithm has been used to achieve pre-emptive avoidance of the NTM, applying ECCD to the resonant surface prior to raising the plasma beta. As the beta is raised beyond the value, which would trigger the mode in the absence of active suppression, the pre-emptive ECCD application prevents the appearance of the mode.

Robustness of RWM stabilization has been observed to be degraded by the effects of ELMs on RWM control response [2]. New plasma-conductor models have been developed based on finite element representation of the DIII-D passive structure, allowing low-order model-based controllers to be designed. Controllers based on these models and including matched filter analysis of magnetic signals and discrimination of the mode using Kalman filters have been found to reduce the impact of ELMs on control performance, and improve robustness of RWM stabilization.

Good dynamic regulation of the magnetic configuration, including boundary, divertor strikepoints, and location of internal flux surfaces, must be maintained in DIII-D to an accuracy of several mm, even in the presence of transient perturbations such as ELMs and sawteeth, over a wide range of shapes and profiles [3]. Axisymmetric control demands in ITER will be even more restrictive, corresponding to shaping and configuration control accuracies on the order of 5-10 times those required in DIII-D (as a fraction of minor radius). Model-based multivariable control design methods allow incorporation of performance requirements in the design process. For DIII-D, such approaches allow designers to trade off aspects of control performance in order to achieve the correct balance required by a given physics experiment. For ITER, such approaches can provide highly optimized control to make best use of actuators whose capabilities are limited by cost constraints. Figure 2 shows a DIII-D experimental demonstration of linear model-based multivariable controllers functioning in concert with a nonlinear algorithm to maximize distance from coil current limits while maintaining good shape and X-point control. Such a linear-nonlinear control system will be essential for ITER in order to provide good control near tightly-constrained operating limits throughout a long pulse discharge.

The DIII-D PCS is a highly flexible multi-cpu general realtime control environment allowing implementation of arbitrarily complex algorithms. The architecture also enables connection of actual PCS hardware and software to detailed simulations to confirm correct code implementation and control performance prior to experimental use. The generality, flexibility, and extensive operational algorithms available in the DIII-D PCS have led to its adoption at fusion experiments worldwide, including MAST, NSTX, KSTAR, EAST, and PEGASUS. The combination of integrated modeling, simulation, and PCS has been used to develop and verify startup and shape control algorithms for several of these devices. Many features and solutions of the DIII-D PCS satisfy requirements for and can provide useful examples in design of the ITER control system.

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- [2] C.M. Fransson, et al., *Phys. Plasmas* **10** (2003) 3961.
- [3] M.L. Walker, et al., "Control of Plasma Poloidal Shape and Position in the DIII-D Tokamak," Proc. 36th IEEE Conf. on Decision and Control, San Diego, CA (1997) 3703.

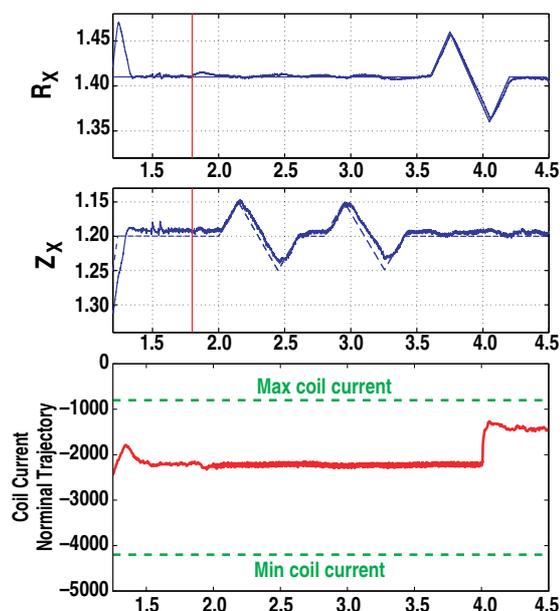


Fig. 2. Experimental application of model-based linear-nonlinear shape controller (dashed=target, solid=result).