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FIRST-PRINCIPLES MODEL-BASED CLOSED-LOOP CONTROL OF THE CURRENT PROFILE DYNAMIC EVOLUTION ON DIII-D

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First-Principles Model-based Closed-loop Control of the Current Profile Dynamic Evolution on DIII-D

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Establishing a suitable current profile has been demonstrated to be a key condition for the achievement of advanced tokamak scenarios with improved confinement and possible steady-state operation. The present approach at DIII-D focuses on creating the desired current profile during the plasma current ramp-up and early flattop phases with the aim of actively maintaining this target profile during the subsequent phases of the discharge. Previous experiments on DIII-D showed that the high dimensionality of the problem, and the strong coupling between magnetic and kinetic variables, call for the design of a model-based, multi-variable controller that takes into account the dynamic response of the full current profile to the different actuators.

Closed-loop model-based profile control experiments were recently performed on DIII-D for the regulation of the poloidal flux gradient profile, $\theta(\hat{\rho},t) = \partial\psi(\hat{\rho},t)/\partial\hat{\rho}$ (inversely proportional to q). Unique characteristics of the control approach are (i) the use of first-principles models for the control synthesis and (ii) the integration of both static and dynamic plasma response models into the design of the feedback controllers. Recent DIII-D experiments constitute the first time ever model-based, first-principles-driven, full-magnetic-profile controllers were successfully implemented and tested in a fusion device.

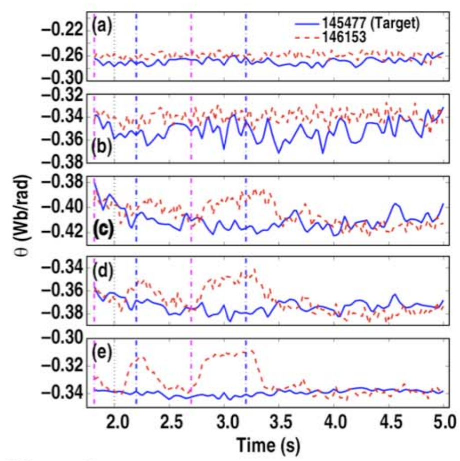

Figure 1: Achieved (dashed red) and target (blue) θ at normalized radii $\hat{\rho}$ =0.3, 0.4, 0.6, 0.8, and 0.9 (top to bottom). Feedback is off for $\Delta t = [1.8, 2.2]$ and $\Delta t = [2.7, 3.2]$ s, and on for $\Delta t = [2.2, 2.7]$ and $\Delta t = [3.2, 5]$ s. Disturbance for $\Delta t = [2, 5]$ s.

In related work at DIII-D, plasma profile response models have been developed using linear system identification. However, as these models are linear, they are only valid around the reference plasma state adopted during the system identification experiment. Therefore, the effectiveness of the controllers designed based on these models may be limited when the plasma state moves away from the reference state. Moreover, as these models are device-specific, dedicated system identification experiments are needed in each device and, potentially, for each control scenario to develop model-based controllers. As an alternative to data-driven modeling, first-principles modeling has the potential of overcoming these limitations. Therefore, a first-principle control-oriented model of the current profile evolution in response to auxiliary heating and current drive systems [Neutral Beam Injection

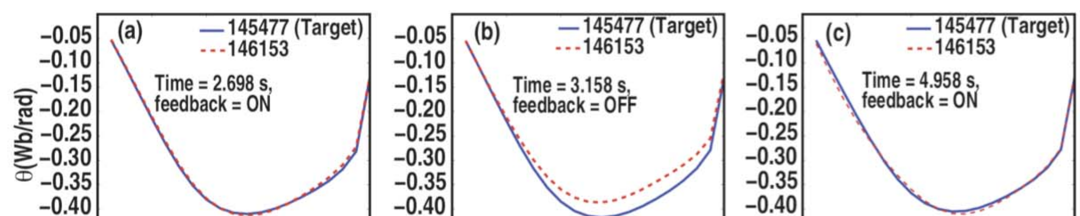

Figure 2: Poloidal flux gradient profile $\theta(\hat{\rho})$ at $t = 2.698\,s$, $t = 3.158\,s$, and $t = 4.958\,s$, respectively, during the flattop phase.

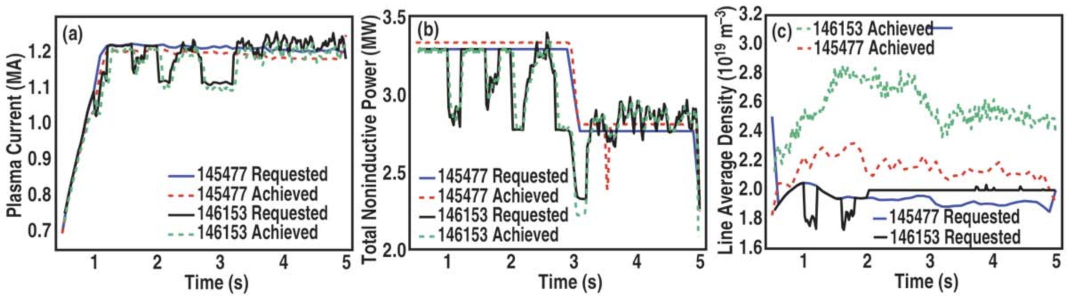

Figure 3: Control trajectory comparison: plasma current, total noninductive power, and line average density.

(NBI)], line-averaged density, and electric field due to induction has been developed for L-mode plasmas. The magnetic diffusion partial differential equation (PDE) is combined with empirical correlations obtained at DIII-D for the temperature and noninductive current to introduce a simplified dynamic model describing the evolution of the poloidal flux ψ profile, and therefore the safety factor q profile, the rotational transform $\iota = 1/q$ profile or the θ profile. This PDE model has the advantages of being 1) easily adaptable to various tokamaks, 2) applicable to various equilibrium configurations and operating scenarios, 3) able to incorporate the nonlinear coupling between the various magnetic and kinetic plasma parameters, and 4) able to explicitly describe the temporal and spatial evolution of the current profile in response to the control actuators.

The control strategy employed to track a desired target profile combines feedforward + feedback control approaches. The feedforward control inputs are computed off-line based on optimization methods to achieve the best possible profile tracking based on the prediction by the PDE dynamic model for a given nominal initial condition and in the absence of external disturbances to the system. To add robustness to the control strategy, the feedback control inputs are computed on-line and added to the feedforward control inputs with the ultimate goal of accounting for the mismatch between the actual and assumed initial conditions, rejecting the effects of external disturbances to the system, and overcoming uncertainties and unmodelled dynamics in the model. A general framework for real-time feedforward + feedback control of magnetic and kinetic plasma profiles has been implemented in the DIII-D Plasma Control System.

An example of the effectiveness of a feedback controller synthesized from the first-principles dynamic model to control the poloidal flux gradient profile evolution $\theta(\hat{\rho},t)$ is shown in Figs. 1 and 2. During DIII-D shot 146153, an input disturbance was introduced to the plasma during the flattop phase of the discharge during the time interval $\Delta t = [2,5]$ s. The feedback controller was turned on and off throughout the discharge to evaluate the effect the disturbance had on the plasma and to determine the ability of the feedback controller to reject the disturbance and regulate the profile around a selected target profile. To ensure feasibility, the previously achieved profile in DIII-D shot 145477 was chosen as the target. The feedback controller was turned on during the time intervals $\Delta t = [1,1.2]$, $\Delta t = [1.6,1.8]$, $\Delta t = [2.2,2.7]$, and $\Delta t = [3.2,5]$ s. The time traces in Fig. 1 clearly show that tight regulation is lost when the feedback controller is turned off. The ability of the feedback controller to reject the effect of the disturbance is also shown in Fig. 2(a) just before the feedback controller is turned off at the time $t = 2.7$ s. During the time interval $\Delta t = [2.7,3.2]$ s, the θ profile drifts away from the target profile due to the disturbance as shown in Fig. 2(b). Finally, the feedback controller was turned on for the remainder of the discharge at the time $t = 3.2$ s and it is once again able to reject the effects the disturbance has on the θ profile as shown in Fig. 2(c). The controller can actuate the total plasma current, the total NBI power, and the line-averaged plasma density to drive the current profile evolution to a desired target profile. It is important to note that the requests made by the feedforward + feedback controller are the references to the respective control loops commanding the physical actuators. The ability of the dedicated control loops to follow the requested actuator demands during DIII-D discharges 145477 and 146153 is shown in Fig. 3. While the control loops commanding the total plasma current and the total NBI power are able to follow the requests very well, the regulation by the control loop commanding the line-averaged density is rather poor (this can be seen as an additional input disturbance). Also shown in Fig. 3 is the modification of the actuator demands by the feedback controller when it is turned on. To regulate the θ profile around the target profile during DIII-D shot 146153, the actuator demands are driven by the feedback controller towards the values achieved in the target shot 145477.

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