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Physics-model-based Control of the Plasma State Dynamics for the Development and Sustainment of Advanced Scenarios in DIII-D PPC

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DIII-D experiment results are presented to demonstrate the potential of integrated physics-model-based q-profile and β_N control for robust and reproducible sustainment of advanced scenarios. The control architecture utilized is a feedforward + feedback scheme where the feedforward commands are computed off-line and the feedback commands are computed online. Good agreement between experimental results and simulation demonstrates the accuracy of the models utilized for physics-model-based control design. Active integrated control of the current density or safety factor profile and β_N provides an important tool for the development and robust sustainment of desired scenarios. In the absence of feedback control, variability in wall conditions and plasma impurities, as well as drift due to external plasma disturbances, can limit the reproducibility of discharges with simple pre-programmed scenario trajectories. Long-pulse steady-state devices such as EAST and ITER in particular have a strong need to actively regulate and sustain particular plasma targets over periods comparable to the discharge time to enable the study of desired regimes, control the proximity to stability limits and maximize the physics output of a limited number of discharges. Our results show the potential of physics-model-based control algorithms to meet these demanding challenges.

The utilized control scheme can be designed to more heavily weight particular regions of interest of the q-profile relative to others, and therefore, can be readily tailored to suit the needs of various physics experiments. At the core of the control algorithms is a nonlinear, physics-based, control-oriented model of the plasma dynamics valid for H-mode scenarios. The model captures the response of the plasma (q-profile and β_N) to the control actuators (total plasma current, auxiliary heating and current-drive sources and line-averaged electron density). A partial differential equation model of the q-profile dynamics is developed by combining the poloidal magnetic flux diffusion equation with physics-based models of the electron density and temperature profiles, the plasma resistivity and the noninductive current sources (both auxiliary and bootstrap). The evolution of the plasma internal energy, which is related to β_N, is modeled by a volume-averaged energy balance equation. The physics information contained in the nonlinear model is embedded into the feedforward and feedback components of the control scheme through advanced model-based control design techniques.

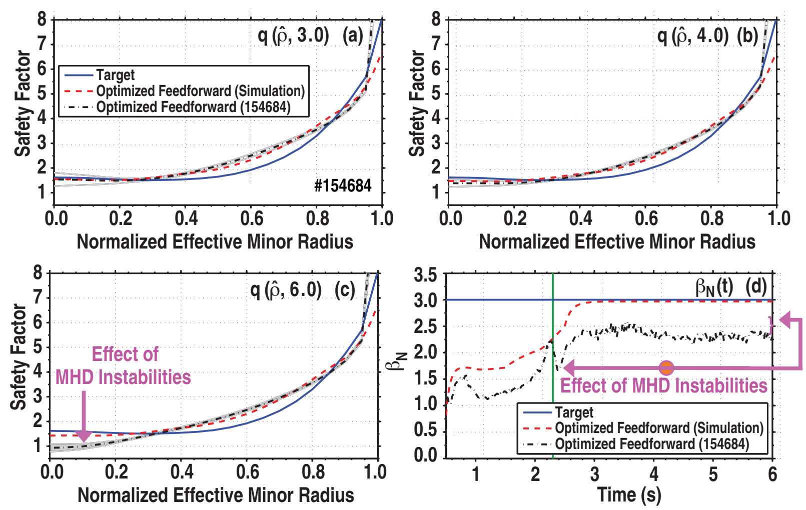

Fig. 1. Simulation and experimental (#154684) testing of optimized feedforward actuator trajectories: (a-c) q-profile at various times and (d) β_N versus time. Approximate error bars for the experimentally measured q-profiles are shown by the gray-shaded regions. The onset of MHD instabilities after 2.3 s during DIII-D shot 154684 is indicated by the solid green line. Note the excellent agreement between the experimentally achieved and simulated q-profiles in (a,b).

Feedforward actuator trajectories were numerically designed to steer the plasma state through the tokamak operating space from a particular initial condition to reach and maintain a target state (q-profile and β_N), while respecting plasma state and actuator constraints, by embedding the physics-based model in a nonlinear optimization algorithm. One of the key physics goals of plasma profile/parameter control is to reach a target plasma state at a desired time and maintain that state to enable the study of desired regimes and make the best use of the discharge. The optimized feedforward actuator trajectories were tested experimentally in DIII-D shot 154684 and through simulation with the physics-based model. The target plasma state was

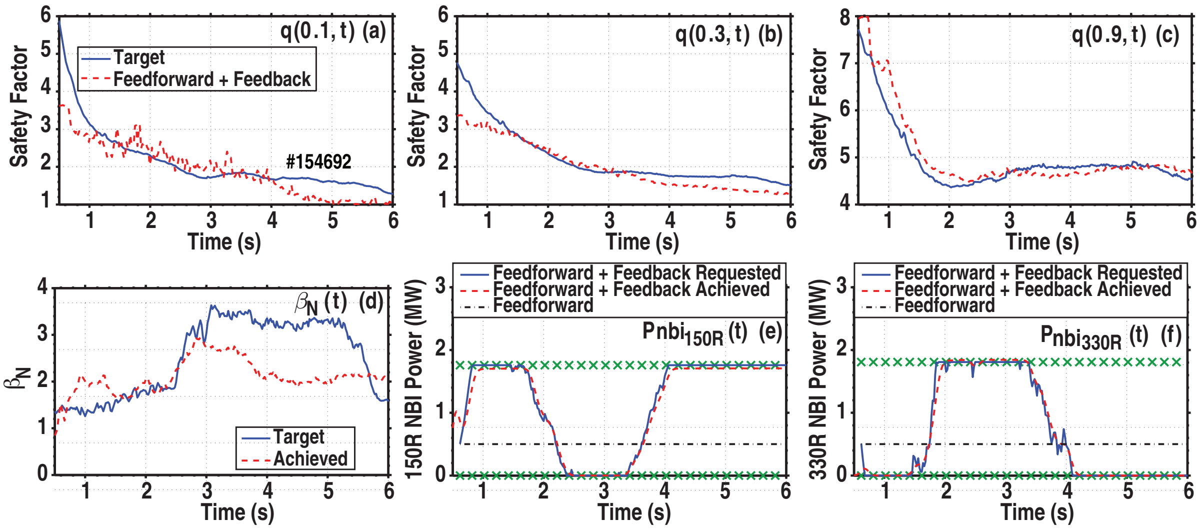

Fig. 2. Experimental testing (#154692) of q-profile feedback controller: (a-c) q vs time at various radial locations, (d) β_N vs time and (e,f) actuator trajectories ($P_{nbi_{150R}}$ - off-axis NBI and $P_{nbi_{330R}}$ - on-axis NBI). Note β_N was not feedback-controlled.

chosen to be the q-profile and β_N experimentally achieved at 3.0 s. in DIII-D shot 150320. A comparison of the target, physics-based model predicted and experimentally achieved q-profiles at various times and a time trace of the achieved β_N is shown in Fig. 1. As shown in the figures, the optimized trajectories were able to drive the experimental plasma as close as possible to the desired stationary q-profile at 3.0 s. However, at approximately 2.3 s, MHD instabilities developed and persisted for the remainder of the discharge. The onset of the MHD modes produced an immediate reduction of β_N [shown in Fig. 1(d)] and resulted in the inability to experimentally achieve the target β_N and maintain the q-profile in the plasma core at the target. However, through simulation with the physics-based model, it was shown (Fig. 1) that the optimized trajectories were able to steer the simulated plasma to the stationary target in the absence of MHD modes.

In another DIII-D discharge, q-profile tracking was obtained exclusively through feedback actuation. A second physics goal of plasma profile/parameter control is to make scenarios more robust and reproducible and to enable controlled variation of specific characteristics of the profiles through feedback to better elucidate physics. A q-profile feedback controller (not including β_N control) was tested in a disturbance rejection experiment in DIII-D shot 154692. The q-profile evolution achieved in DIII-D shot 154358 was chosen as the target. The disturbance introduced to the plasma was to delay the H-mode transition time, which generated a significant perturbation in the initial q-profile at 0.5 s. Also the feedforward component of the control input was frozen after 1.6 s, therefore, the achieved profile regulation was obtained exclusively through feedback. Time traces of q at various radial locations and of the achieved β_N are shown in Fig. 2. As shown in the figures, the controller was able to reject the effects of the initial condition error and drive the q-profile to the target evolution during the time interval $t \in [0.5, 3.5]$ s. The controller used the total plasma current to regulate the q-profile near the plasma boundary and modulated the mix of on-and-off axis auxiliary current-drive to track the target q-profile in the plasma core [shown in Fig. 2(e,f)]. However, even though the feedback controller requested the maximum amount of off-axis auxiliary current-drive during the time interval $t \in [4.0, 6.0]$ s, the q-profile in the plasma core was unable to be maintained at the target. As shown in Fig. 2(d), the achieved β_N was relatively far away from the target during the approximate time interval $t \in [3.0, 6.0]$ s. This may have resulted in a lower bootstrap current, which in turn may have contributed to the inability to maintain the target q-profile in the plasma core, during the feedback-controlled experiment.

The presented advances provide tools to study and quantify the capability of model-based profile control to improve scenario robustness. These control algorithms also enable detailed study of the accuracy and validity of the relevant models themselves and can help clarify physics aspects important to robust scenario execution, such as the need to simultaneously achieve a target q-profile and β_N. Model-based control is motivated by the coupled, nonlinear, multivariable, distributed plasma dynamics. Controllers derived from a model of these dynamics know in which direction to actuate to generate a desired plasma response and can be designed to share the actuation capabilities. During the upcoming DIII-D campaign, it is planned to simultaneously control the q-profile and β_N in feedback experiments and to better understand and mitigate the effect of disturbances (such as the illustrated β_N drop) subject to the limited available actuation.

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