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Integrated Magnetic and Kinetic Control of Advanced Tokamak Scenarios on DIII-D Based on Data-Driven Models ITR

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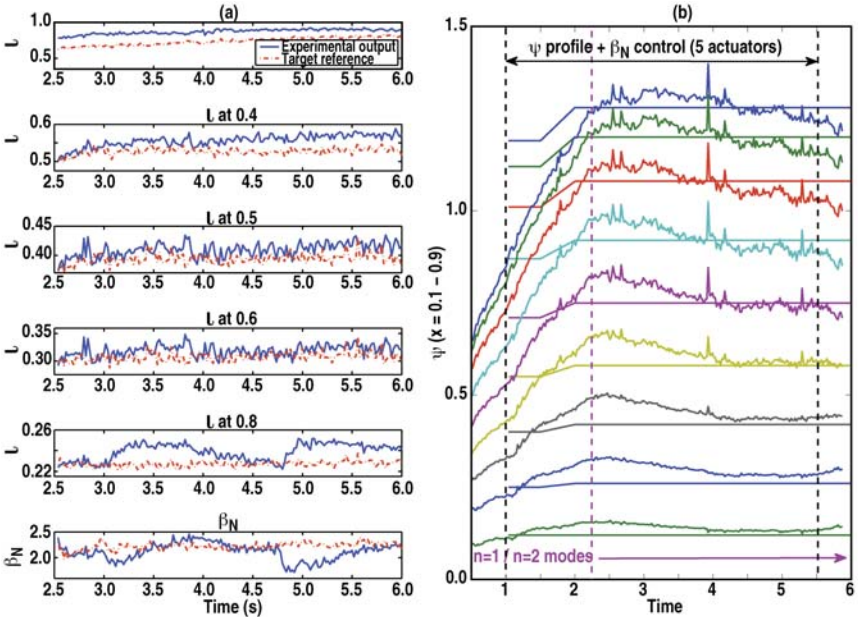
Closed-loop model-based profile control experiments were recently performed on DIII-D for the regulation of (a) the poloidal flux profile, $\psi(x)$, (b) the inverse of the safety factor profile, $\iota(x)=1/q(x)$, and (c) either the poloidal flux profile or the inverse of the safety factor profile together with the normalized pressure parameter, β_N. *These are the first profile control experiments integrating magnetic and kinetic variables.* The description of these experiments



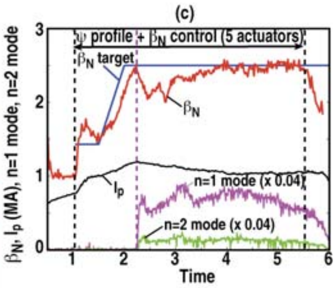


Fig. 1. (a) DIII-D shot 147707. Experimental (blue) and target (red) $\iota(x)$ profile at x=0.2, 0.4, 0.5, 0.6 and 0.8 and β_N. (b) DIII-D shot 146463. Experimental and target $\psi(x)$ profile at x=0.1, 0.2, … 0.9. (c) DIII-D shot 146463. Experimental (red) and target (blue) β_N, plasma current (black), n=1 (magenta) and n=2 (green) mode amplitudes.

and the discussion of the results will constitute the main part of the paper.

The development on ITER of hybrid and steady state operation scenarios with high neutron fluence implies the control of improved-confinement, high-β_N, high-bootstrap plasmas that are currently obtained in various tokamaks, for durations that hardly exceed the resistive diffusion time. Real-time control of plasma parameters such as the current profile, toroidal rotation and pressure is important for extrapolating these advanced tokamak (AT) scenarios to steady state operation. The development of profile control is also motivated by the potential gain that it could yield in running stable and reproducible AT discharges, in order to study the physics of AT scenarios for ITER. The integrated model-based approach presented here is being developed under the framework of the International Tokamak Physics Activity for Integrated Operation Scenarios (ITPA-IOS) and relies on generic system identification and control methodologies. The determination of device-specific, data-driven, control-oriented models that are needed to compute the optimal controller matrices, was performed on JET, JT-60U and DIII-D [1]. It was thus shown that the coupled response of the relevant parameter profiles to variations of specific heating and current drive (H&CD) actuators could indeed be satisfactorily identified from experimental data where the various actuators were randomly modulated. These data-driven control-oriented models were used to synthesize integrated magnetic and kinetic profile controllers with different levels of model integration for DIII-D.

The chosen reference plasma state around which the data-driven models were identified was that of a 1.8 Tesla, β_N-controlled AT scenario, at a central plasma density, $n_{e0} \approx 3.5\times10^{19}$ m^{-3} and plasma current, I_p = 0.9 MA. The neutral beam injection (NBI) and electron cyclotron current drive (ECCD) systems provided the heating and current drive sources for these experiments. Available beamlines and gyrotrons were grouped to form, together with the plasma surface loop voltage, V_{ext}, or current, I_p, five independent H&CD actuators: (a) co-current NBI power, P_{CO}, (b) counter-current NBI power, P_{CNT}, (c) balanced NBI power, P_{BAL}, (d) total ECCD power from all gyrotrons in an off-axis current drive configuration, P_{EC}, and (e) V_{ext} or I_p.

Control of $\iota(x)$ and simultaneous control of $\iota(x)$ and β_N were performed through a mixed-sensitivity robust control algorithm. A singular value decomposition (SVD) of the steady-state plasma response model is carried out to decouple the system and identify the most relevant control channels. The dynamic plasma response model is then explicitly integrated into the synthesis of a feedback controller that minimizes the reference tracking error and rejects external disturbances with minimal control energy and guaranteed bounds of robustness. The feedback controller is then augmented with an anti-windup compensator, which keeps the given profile controller well-behaved in the presence of magnitude constraints in the actuators and leaves the nominal closed-loop unmodified when no saturation is present. Figure 1 (a) shows an example where the controller was switched on from t=2.5 s until t=4.75 s and from t=5 s until t=6 s. Disturbances in I_p, P_{CO}, P_{BAL}, *and* P_{EC} were artificially introduced at t=3 s. The target and achieved values of $\iota(x)$ at x = 0.2, 0.4, 0.5, 0.6, 0.8 and of β_N can be compared. Good tracking and disturbance rejection was observed. In particular, a clear recovery was observed after the injection of disturbances and the momentary shutdown of the feedback controller.

Control of $\psi(x)$ and simultaneous control of $\psi(x)$ and β_N were performed through a proportional-plus-integral near-optimal control algorithm. This controller offers a good compromise between performance and actuator power, and takes advantage of the different time scales involved in magnetic and kinetic diffusion processes. It is optimal to order $O(\varepsilon^2)$ where ε is the typical ratio between the energy confinement and the resistive diffusion times. The integral feedback is used to drive the plasma to the closest self-consistent equilibrium state to the prescribed target state, i.e., to minimize

$$I_\infty = \int_0^1 \left[\psi(x) - \psi_{\text{target}}(x)\right]^2 dx + \lambda^2 \left[\beta_N - \beta_{N,\text{target}}\right]^2$$

given the constraints on the available actuators. Figure 1(b,c) shows an example where the controller was switched on at t=1 s, i.e. during current ramp-up, until t=5.5 s. The target and achieved values of $\psi(x)$ at x = 0.1, 0.2, … 0.9 and of β_N can be compared. Despite an n=1 MHD mode from t=2.3 s to the end, $\psi(x)$ and β_N control was successful and the cost function I_∞ stayed near its lowest value from about t=4 s until the end of the control phase.

Finally, time-dependent ITER simulations in which the nonlinear plasma response to the control actuators is modelled using a numerical transport code have also been performed to investigate the potential of model-based controllers for plasma control in ITER long pulse scenarios and burning plasmas. Results for an ITER hybrid scenario similar to those obtained in the DIII-D experiments will be shown.

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[1] D. Moreau, *et al*., Nucl. Fusion **51** (2011) 063009.