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FEEDBACK CONTROL OF THE SAFETY FACTOR PROFILE IN DIII-D ADVANCED TOKAMAK DISCHARGES

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Feedback Control of the Safety Factor Profile in DIII-D Advanced Tokamak Discharges* EX-C

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A key feature of an advanced tokamak (AT) discharge is a safety factor (q) profile that is consistent with both magnetohydrodynamic (MHD) stability at high toroidal β and a high fraction of the self-generated bootstrap current. The approach taken toward establishing an AT discharge in the DIII-D tokamak is to create the desired q profile during the plasma current ramp-up and early flattop phases, with the aim of maintaining this "target" profile in steady-state during the subsequent high β phase using noninductive current drive and bootstrap current. In this paper we report results from successful experiments at DIII-D on active feedback controlled formation of the target q profile. The use of feedback control is motivated by improved discharge reproducibility and optimization of the target q profile for the high β phase.

The goal of the feedback is to control the time evolution of the on-axis [$q(0)$] or minimum (q_{min}) values of q beginning with the relatively high values just after the plasma breakdown to reproducibly arrive at the values to be sustained in steady-state, $1.5 < q_{min} < 2.5$ and $q(0) - q_{min} \approx 0.5$, at the beginning of the high β phase. The feedback control (Figs. 1, 2) is implemented during and just following the period of ramp-up of the plasma current, using electron heating to modify the plasma conductivity, σ, and thus the rate of relaxation of the inductive component of the plasma current. This concept of using changes in the σ profile to modify the current profile evolution is unique to DIII-D experiments and contrasts with

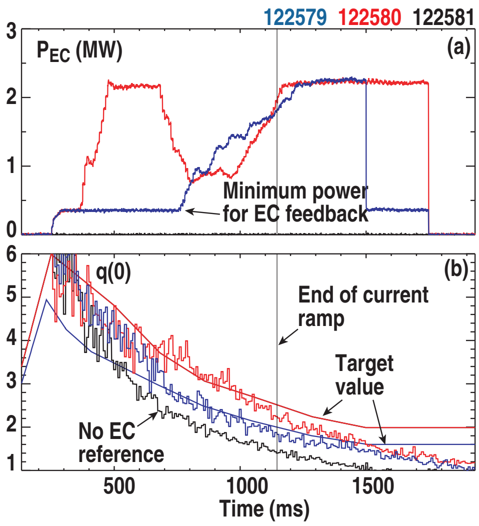

Fig. 1. Closed loop feedback control of the on-axis q in L-mode discharges using ECH at $\rho \approx 0.4$ as the actuator (red and blue curves). (a) The gyrotron power. (b) Comparison of the feedback target values (smooth curves) to the real time calculation of q.

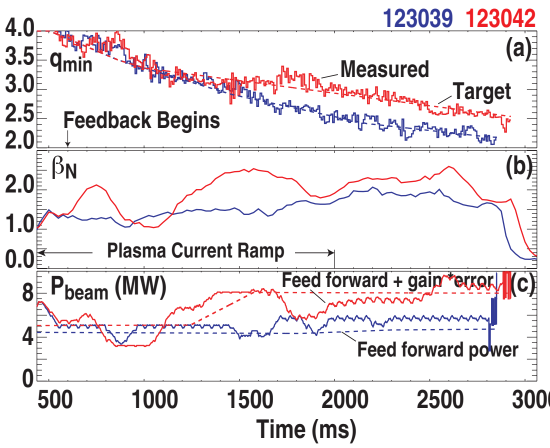

Fig. 2. Two examples of closed loop control of the minimum q value in H-mode discharges using neutral beam heating as the actuator. (a) A comparison of the feedback target values (dashed curves) with the real time calculation of q_{min}. (b) β_N. (c) A comparison of the preprogrammed feed forward neutral beam power (dashed curves) with the power actually used for feedback control.

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maintenance of a constant current profile in steady-state, which utilizes sources of localized current drive and which has been the focus of experiments at other tokamaks. In L-mode and H-mode discharges, feedback control of q is effective with the appropriate choice of either off-axis ECH or neutral beam heating as the actuator. The q profile is calculated in real time from a complete equilibrium reconstruction fitted to external magnetic field and flux measurements and internal poloidal field measurements from the motional Stark effect diagnostic. Transport code predictions of the time evolution of the q, plasma current, and toroidal electric field profiles (Fig. 3) are used to guide the development of the real-time feedback control algorithm.

In L-mode, electron heating is effective for modification of the time evolution of $q(0)$ but, because of the relatively peaked T_e and σ profiles, the capability to change the evolution of q_{min} is limited. Two examples of feedback control of $q(0)$ in L-mode discharges using off-axis ECH are compared in Fig. 1 to a case without electron cyclotron heating (ECH). Both feedback control cases demonstrate the capability to have $q(0)$ follow a preprogrammed evolution at values above that obtained without additional heating. The available ECH power limited the control effectiveness after the plasma current ramp-up when $q(0)$ dropped below the programmed level and at the beginning of the discharge when there were mismatches between the target and actual values of $q(0)$ after the discharge breakdown.

The value of q_{min} has been controlled at relatively high values and for long duration using neutral beam heating in H-mode discharges [Fig. 2(a)]. The ability to modify the evolution of q_{min} is a result of the broad T_e profile in H-mode. Because of the increased actuator power that is available using neutral beams, the actual values of q_{min} were maintained close to the programmed levels for almost 1 s after the end of the plasma current ramp-up. Because neutral beams heat ions as well as electrons and provide particle fueling, the increase in β_N [Fig. 2(b)] for a given increase in conductivity is larger than with ECH so that it is relatively easy to reach a stability limit, an effect that must be taken into account by the real-time controller.

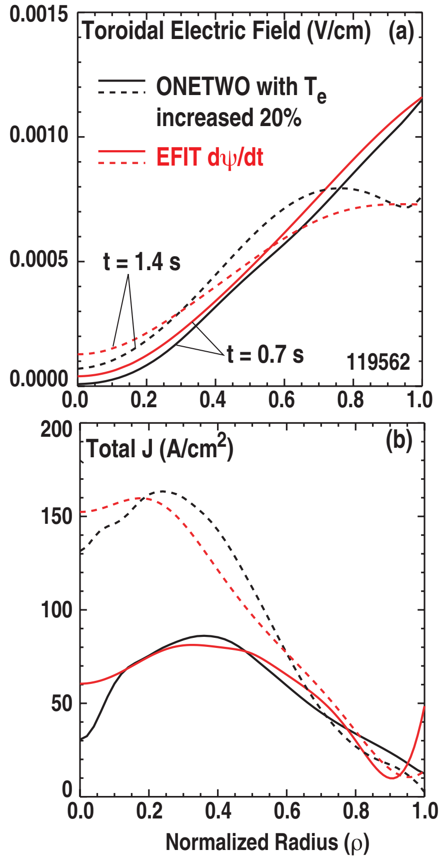

Fig. 3. Comparisons of predictions from the ONETWO transport code of (a) the toroidal electric field and (b) the total current density with the experimental values obtained from the EFIT equilibrium reconstruction code for an L-mode discharge. Improved agreement is obtained by using values of T_e slightly increased above the experimental values.

Comparisons of experimental measurements and transport code predictions of the time evolution of the tokamak equilibrium are used to validate transport codes for use in testing of real-time feedback control algorithms. Given an initial experimental equilibrium, measured density and temperature profiles, the plasma boundary shape, and models for bootstrap current, beam-driven current and conductivity, the transport code predicts the evolution of the plasma current profile. Figure 3, for example, illustrates the reasonable agreement between the experiment and the prediction in a simple case with constant heating power. Additional code validation will include the dynamics of the q profile evolution by comparison to measurements of the responses of $q(0)$ and q_{min} to modulation of the actuator power.

Thus far, the controller for q has utilized simple proportional gain with the requested actuator power equal to a preprogrammed feed-forward value plus the error in q multiplied by the gain [Fig. 2(c)]. Improved real-time controllers are being developed by including the feedback algorithm into the transport code simulation. The goal is a controller that can maintain the target q evolution without requiring detailed preprogramming of the feed-forward actuator power, with relatively low gain so that excursions in β_N can be minimized, and with relatively infrequent measurements of the q profile.