Control of DIII-D Advanced Tokamak Discharges

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A key goal in control of an advanced tokamak (AT) discharge is to maintain safety factor (q) and pressure profiles that are compatible with both MHD stability at high toroidal beta and a high fraction of the self-generated bootstrap current. This will enable high fusion gain and noninductive sustainment of 100% of the plasma current for steady-state operation [1]. As part of the DIII-D AT research program, the necessary control tools and actuators are being tested both separately and integrated together in an AT discharge. We report results from the first demonstrations of active feedback control of the q profile evolution and progress towards enabling active control of the pressure profile.

The approach taken toward establishing an AT discharge in DIII-D is to create the desired q profile during the plasma current ramp-up and early flattop phases and sustain it during the subsequent high beta phase using off-axis ECCD combined with bootstrap current and neutral beam current drive. An example is shown in Fig. 1. To maintain relatively high q_{min}, an H-mode transition is induced at 430 ms and, in this case, to improve reproducibility feedback control of β_N was used beginning at 500 ms. The high beta phase begins at 3400 ms when $q_{min} \approx 1.7$ ($q_{95} \approx 5$). In discharges similar to this, with up to 2.5 MW of off-axis electron cyclotron current drive (ECCD) and up to 15 MW neutral beam injection, ~100% of the plasma current has been sustained noninductively for 1 s at high beta ($\beta = 3.6\%$, $\beta_N = 3.4$) above the no-wall stability limit. During the high performance phase, accurate feedback control of β_N allows operation at β values near the ideal-wall stability limit [2].
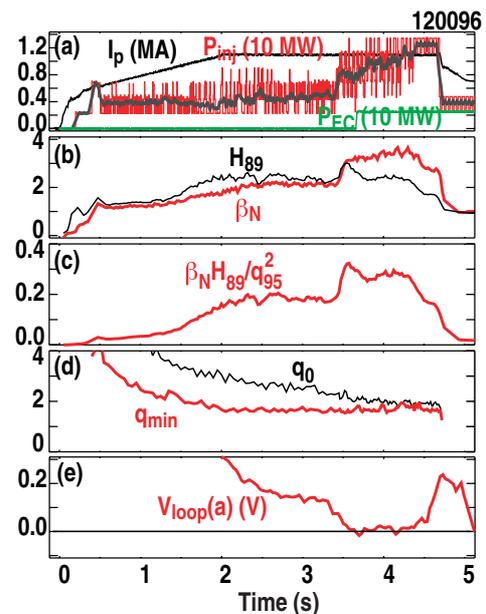

Fig. 1. The time evolution of a DIII-D AT discharge with 100% of the plasma current driven noninductively.

The initial evolution of the q profile has been the focus of the first feedback control experiments. The goal is to control the q profile evolution beginning with the relatively high values just after the plasma breakdown, so that it reproducibly arrives at the profile 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 beta phase. Here, q_{min} is the minimum q value and $q(0)$ is the value on axis. During the first portion of the discharge, the rate of evolution of the current density profile, and thus the q profile, can be modified through changes in the conductivity with electron heating [3], changes in the plasma current ramp rate or noninductive current drive. Feedback control is necessary in order to adapt to variations in the current profile created at discharge breakdown and in the density and impurity profiles during the current ramp-up.

The largest modifications in the q profile evolution are obtained through changes in T_e. This is illustrated in Fig. 2 in which the effect of the value of T_e is compared for L-mode [Figs. 2(a-c)] and H-mode [Figs. 2(d-f)]. In three of the cases shown, feedback controlled ECH resonant at normalized radius $\rho \approx 0.4$ is used to hold T_e at a constant level, while in the other two cases no ECH is applied. In the L-mode cases, the T_e profile, and thus the conductivity profile, is relatively peaked so the strongest effect of increasing T_e is to reduce the decay rate of $q(0)$. The evolution of q_{min}, located near the mid-radius, is only slightly affected. In the H-mode case, the T_e profile is much broader as a result of the edge-region transport barrier resulting in relatively large conductivity outside the radius of q_{min}. Both q_{min} and $q(0)$ are significantly increased when T_e is raised. In addition, the q values are much higher in the H-mode cases for a longer duration compared to the L-mode discharges for comparable mid-radius values of T_e. So,
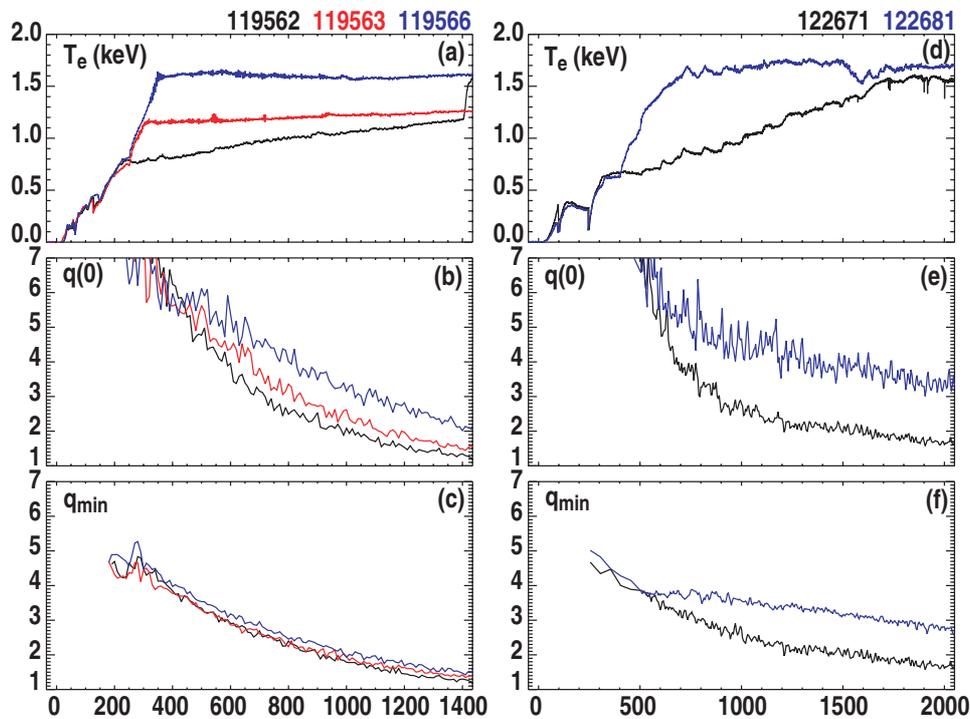

Fig. 2. Time evolution of $q(0)$ and q_{min} in (a-c) L-mode and (d-f) H-mode for several values of T_e.

the choice between L-mode and H-mode is also an effective means to modify the q profile because of the change in the shape of the conductivity profile.

The use of ECCD at $\rho \approx 0.4$, so that the effect of current drive is added to the effect of increasing T_e, resulted in a relatively small modification to the evolution of q(0) and essentially no change in the q_{min} evolution. This is illustrated by the comparison between co- and counter-ECCD at 2.3 MW in Fig. 3. The limited effect is a result of the small amount of current that is driven at the relatively low T_e during the I_p ramp.

Closed loop control of the q evolution has been successfully tested in both L-mode and H-mode using either ECH at $\rho \approx 0.4$ or neutral beam power as the actuator for modification of T_e. The q feedback control makes use of real time equilibrium reconstruction [4] including fitting of motional Stark effect (MSE) magnetic field pitch angle measurements at up to 26 radial positions with correction for the effect of the radial electric field. Spline parameterization of the current profile is used to allow accurate identification of q profiles with negative central magnetic shear. Full profiles of q are available in real time at 4-8 ms intervals.

Two examples of feedback control of q(0) in L-mode discharges using off-axis ECH are compared in Fig. 4 to a case without ECH. The control here is on q(0) because, as illustrated in Fig. 2, there is little ability to modify q_{min} using electron heating with the conductivity profiles characteristic of L-mode. Both feedback control cases demonstrate the capability to have q(0) follow a preprogrammed evolution at values above that obtained without the additional heating until the ECH saturates at the maximum available power.

Fig. 3. Time evolution of q(0) and q_{min} in H-mode discharges with co (black curves) and counter (red curves) ECCD.

Feedback control of q_{min} in two H-mode discharges using neutral beam power as the actuator is shown in Fig. 5. Here, because of the increased actuator power that is available, the actual values of q_{min} were maintained close to the programmed levels for almost 1 s after the end of the I_p ramp-up. The duration of the feedback control in this case was limited only by the available pulse length of the neutral beam that is required for the MSE diagnostic. Because neutral beams heat ions as well as electrons and provide particle fueling, the increase in β_N for a given increase in conductivity is larger than with ECH so that it is relatively easy to reach a beta limit resulting in an instability that causes significant uncontrolled modifications of the current profile.
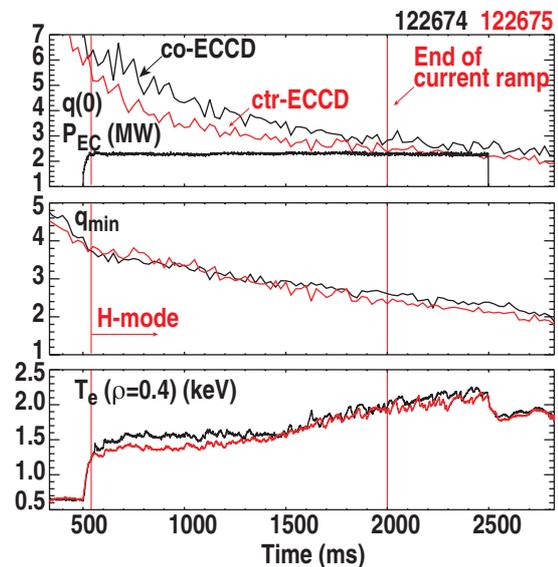
The shape of the pressure profile plays a key role in the ability to operate at high beta. Modeling has demonstrated that stable operation with $\beta_N = 5$ with $q_{min} > 2$ should be possible with a sufficiently broad pressure profile [5], while in the experiment [2] $\beta_N = 4$ with $q_{min} = 2$ has been achieved thus far with $P(0)/\langle P \rangle = 2.3$. With this motivation, tools for pressure profile control are being implemented. A 32 channel profile of T_e from the ECE diagnostic and n_e and T_e from Thomson scattering are presently available in real time. Real time measurement of the T_i and rotation profiles from the CER diagnostic is being implemented. Modification of two neutral beam sources to counter-injection is planned to facilitate pressure and rotation control.

In summary, then, AT discharges have been produced with approximately 100% of the plasma current sustained noninductively for 1s at high beta ($\beta = 3.6\%, \beta_N = 3.4$). To improve reproducibility of these discharges and facilitate the formation of the optimum target q profile for the high performance phase, feedback control of the q profile evolution during the initial portion of the discharge is being developed. In L-mode and H-mode discharges, feedback control of q is effective using either off-axis ECH or neutral beam heating as the actuator. Capability for control of the pressure profile is also being added to the real time control system.

Fig. 4. Closed loop feedback control of q(0) in L-mode discharges using ECH at $\rho \approx 0.4$ as the actuator.

Fig. 5. Closed loop co f q_{min} in H-mode discharges using neutral beam heating as the actuator.

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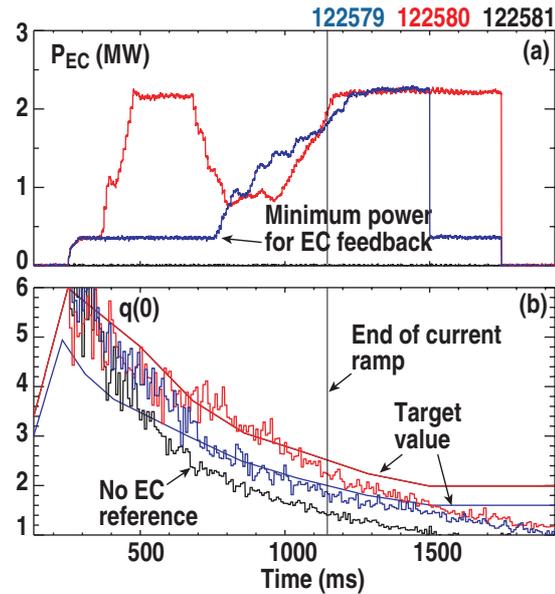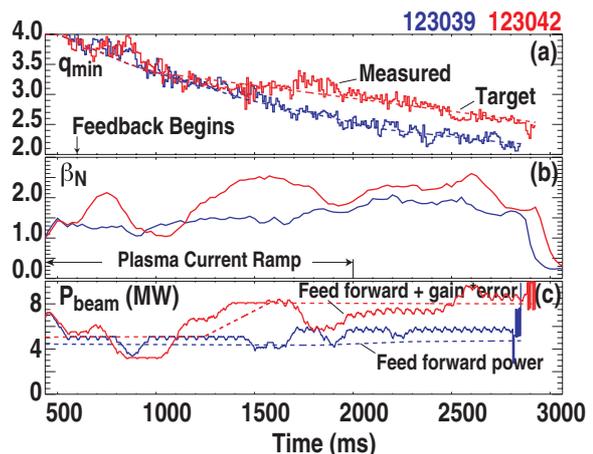[5] M.A. Makowski, *et al.*, *Proc. of the 30th European Conf. on Controlled Fusion and Plasma Physics, St. Petersburg*, Vol. 27A (2003, ECA) P-2.113.