Progress Toward Sustained High-Performance Advanced Tokamak Discharges in DIII–D

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Key elements of a sustained advanced tokamak discharge in DIII–D are a large fraction of the total current from bootstrap current (f_{BS}) and parameters that optimize the capability to use electron cyclotron current drive (ECCD) at $\rho \approx 0.5$ to maintain the desired current profile [1–4]. Increased f_{BS} results from increasing both the normalized beta (β_N) and the minimum value of the safety factor (q_{min}). Off-axis ECCD is, for the available gyrotron power, optimized at high β_N, high electron temperature (T_e) and low electron density (n_e). As previously reported [2–4], these required elements have been separately demonstrated: density control at high β_N with $n_e \leq 5\times10^{19}$ m^{-3} using divertor-region pumping, stability at high β, and off-axis ECCD at the theoretically predicted efficiency. This report summarizes recent work on optimizing and integrating these results through evaluation of the dependence of the beta limit on q_{min} and q_{95}, exploration of discharges with relatively high q_{min}, testing of feedback control of T_e for control of the q profile evolution, and modification of the current profile time evolution when ECCD is applied.

Discharges with q_{min} just above 1.5 have been the focus of much of the previously reported advanced tokamak work in DIII–D [2–4]. These discharges have many of the desirable parameters, $\beta_N \approx 4$, and $H_{89} \approx 3$ (ratio of τ_E to ITER L–mode scaling), with β_N $H_{89} > 10$ sustained for about 0.6 s ($\approx 5 \tau_E$). The value of f_{BS} is about 65% and β_N reaches 6 ℓ_i, close to the predicted limit for the ideal n = 1 kink mode with an ideal wall at the DIII–D vessel. The ideal no-wall β_N limit is about 4 ℓ_i. Achievement of sustained β_N values well above the no-wall limit has been aided by improved correction of intrinsic nonaxisymmetric fields, allowing toroidal plasma rotation above the level required to stabilize the n = 1 resistive wall mode (RWM) [5]. These discharges were produced with L–mode during the plasma current ramp-up. The value of q_{min} plays an important role as the high performance phase in these discharges is normally terminated by the onset of an m = 2/n = 1 tearing mode as q_{min} decreases to about 1.5.

The achievable β_N in discharges with $q_{min} \approx 1.5$ has been found empirically to depend on the edge safety factor, q_{95}. By increasing q_{95} from 4.0 to 4.8 (by increasing B_T at fixed I_p), reproducible β_N increased from 3.4 to 4. This observation contrasts with predictions from ideal MHD modeling from which a 5%–10% reduction in the β_N limit to the n = 1 mode is predicted for the same change in q_{95}. The improved β_N values in the experiment appear to result primarily from improved ability to operate close to the ideal wall β_N limit when B_T is increased. This is determined from the n = 1 growth rates as a function of the position of the ideal conducting wall calculated by the ideal MHD stability code GATO. The $q_{95} = 4$, $\beta_N = 3.4$ case benefited little from wall stabilization, as the prediction is that a wall located at

2.5 times the minor radius would be sufficient for stability. In contrast, the q_{95}=4.8, β_N=4 case requires a conducting wall at approximately the position of the DIII–D vessel for a prediction of stability, and so is close to the ideal wall limit.

Recently the ability to reach the high β_N phase of the discharge with $q_{min} > 2.5$ was demonstrated by inducing H–mode early in the plasma current ramp. In H–mode, T_e is higher so the penetration of the ohmic current to the discharge core is slower, resulting in higher values of q_{min}. An example of the time evolution of this type of discharge is shown in Fig. 1. At comparable values of β_N, discharges with higher values of q_{min} would be expected to have a higher fraction of the plasma current resulting from bootstrap current [1], making this discharge attractive for an advanced tokamak scenario. The $q_{min} \approx 2.5$ discharges have the additional advantage that the 2/1 tearing mode does not terminate the high performance phase as in the $q_{min} \approx 1.5$ cases resulting in an increased duration of high performance. This is probably because the $q = 1.5$ and $q = 2$ surfaces are not present in the discharge. However, the advantage of increased q is compromised by an observed reduction

Fig. 1. Time evolution of parameters in a high q_{min} discharge created with an early H–mode.

in the achievable β_N in these discharges to about 2.8 for $q_{min} > 2.5$ (diamonds in Fig. 2). Thus f_{BS} is lower, at approximately 40%, than in the higher beta discharges with $q_{min} \approx 1.5$.

A study was made of the change in the beta limit that accompanied the increased values of q_{min}. Although, the beta limit is ultimately determined by ideal MHD modes stabilized by the effect of the conducting vacuum vessel wall, it is difficult to determine solely from the experiment how close a discharge is to this ideal-wall limit as many factors affect the achievable beta. So, the focus was placed on the no-wall beta limit. An initial modeling study was performed using equilibria created with the TOQ code with typical H–mode current and pressure profiles and evaluated for stability using the GATO code. The results are shown by the triangles in Fig. 2. There is a general downward trend in the beta limit as q_{min} is increased, although there is some increase predicted when the $q = 2$ surface is first removed from the equilibrium.

The experimental test made of the dependence of the no-wall beta limit on q_{min} depends on the predicted and observed [5] enhancement of the resonant interaction between the intrinsic nonaxisymmetric fields and a rotationally stabilized n = 1 RWM when beta is above the no-wall limit. This is illustrated in the example pair of discharges in Fig. 3. In the experiment, feedback control of the neutral beam power is used to regulate β_N at a constant value [Fig. 3(a)] and the current in the external field symmetrization coil is reduced to zero [Fig. 3(c)]. If beta is above the no-wall limit, the enhanced drag of the nonaxisymmetric field on the plasma causes a strong decrease in the toroidal rotation [the solid curve in Fig. 3(d)]. The rotation is reduced below the critical value for stabilization of the RWM and an n = 1 mode grows [Fig. 3(e)]. If β_N is below the no-wall limit when the symmetrization current is reduced, there is a small reduction in the toroidal rotation, but there is no instability
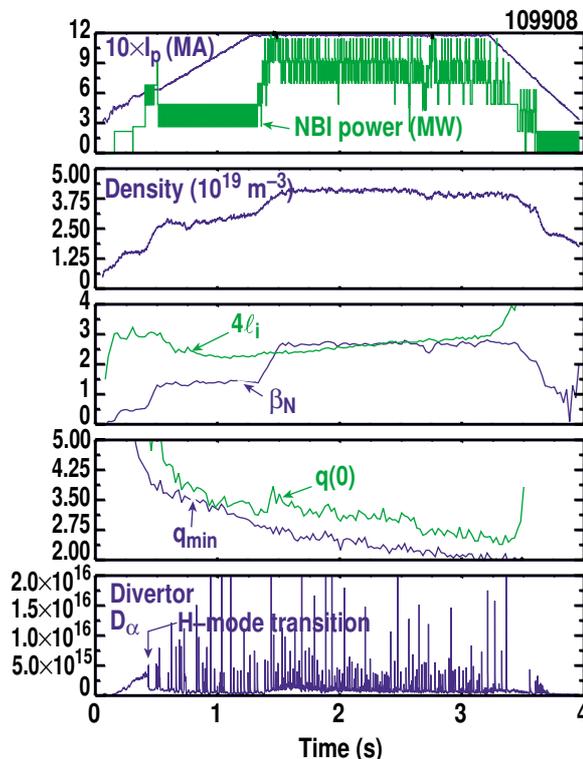
growth (dashed curves in the figure). The square symbols in Fig. 2 summarize the dependence of the measured β_N limit on q_{min}. There is a significant decrease as q_{min} is increased, similar to the trend predicted by the modeling. The quantitative agreement between the experiment and the theoretical prediction should improve when the current and pressure profiles in the model equilibria are improved to match the profiles from the experimental discharges.

The initial current profile in these advanced tokamak discharges is adjusted by modifying the early time evolution of the heating power, density, or current ramp rate. One of the principle effects of these adjustments is to change the time evolution of T_e, strongly affecting the conductivity $\left(\propto T_e^{1.5}\right)$ and the rate of current penetration. Active control of T_e is a more direct method to control the q profile evolution, as has been demonstrated in DIII–D using either ECH or neutral beams as the feedback controlled heating source. Figure 4 shows an example where the T_e evolution was controlled to be the same as was obtained in a high performance discharge in which the neutral beam heating power was preprogrammed. Feedback control of either ECH or neutral beam power duplicated well the T_e time evolution. As a result, the q profile at the end of the plasma current ramp-up was approximately the same in all three cases (Fig. 4). Using T_e control by ECH, the electron density can be significantly reduced during the current ramp-up while the q profile obtained is nearly unchanged, resulting in lower density during the high β_N phase and thus conditions that should produce more efficient ECCD.

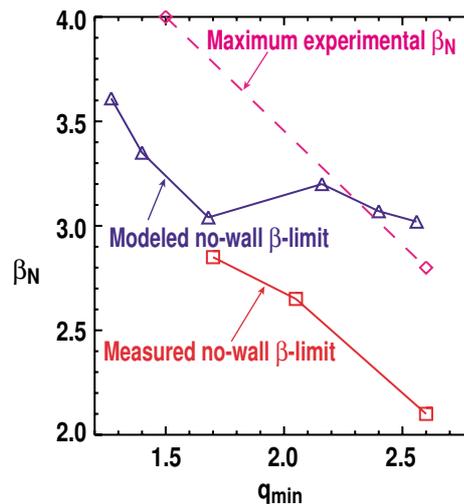Modification of the time evolution of the

Fig. 2. Dependence of the measured no-wall beta limit (squares), the modeled no-wall limit (triangles) and the maximum experimental β_N (diamonds) on q_{min}.

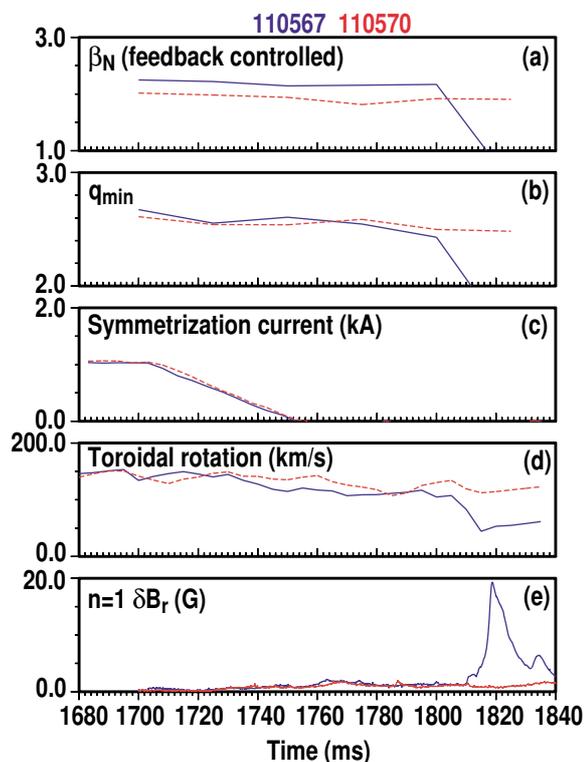

Fig. 3. An illustration of the technique for measurement of the no-wall beta limit.

q profile using off-axis ECCD has been demonstrated, as illustrated in Fig. 5. A simulation of the expected effect of adding 2.5 MW of ECCD in a narrow region at $\rho = 0.4$ is shown in Fig. 5(a). The simulation predicts an increase in q at $\rho = 0$, and an initial small decrease in q_{min} followed by a long phase in which q_{min} decreases more slowly than would have occurred if the ECCD was not present. The experimental results are shown in Fig. 5(b) where two discharges are compared, with and without ECCD applied. The significant features of the simulation, the rise in $q(0)$ and the initial small drop in q_{min} followed by a period with only a
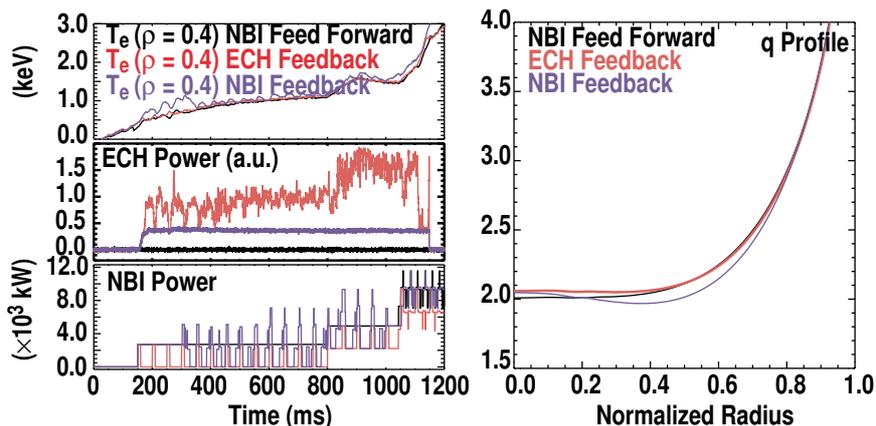
Fig. 4. An example of active T_e control using either ECH or neutral beam heating and the resulting q profiles as compared to a case with preprogrammed neutral beam power.

slow decrease, are present also in the experiment.

In summary, then, important progress has been made toward integrating the key elements of an advanced tokamak discharge in DIII–D. Because of the importance of operation at high β, comparisons of the beta limits to theoretical predictions have been studied. Operation at increased values of q_{min} has been explored in order to find the optimum regime for high f_{BS}. Active control of T_e and modification of the time evolution of the q profile using ECCD have been demonstrated.

ACKNOWLEDGMENT

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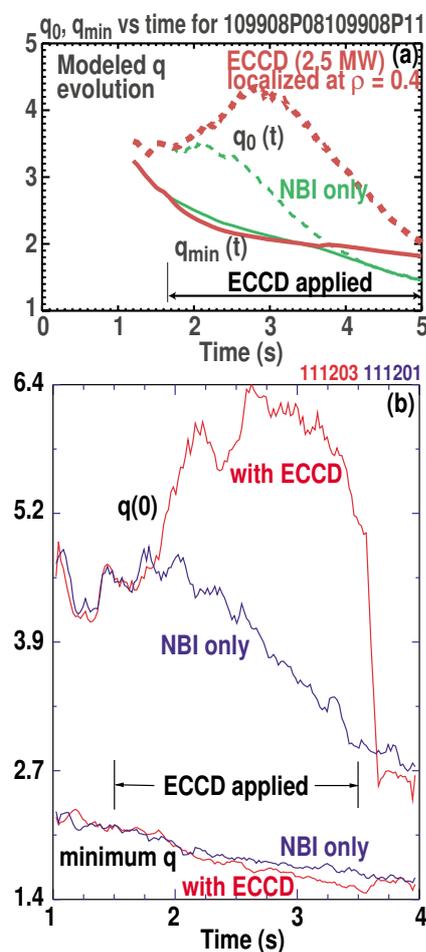[5] A.M. Garofalo *et al.*, Phys. Plasmas **9**, (2002) 1997.

Fig. 5. (a) Modeled time evolution of q in the discharge shown in Fig. 1 with ECCD added. Thin lines have only NBI, thicker lines have ECCD. (b) Time evolution of q in the experiment with and without ECCD.