Optimizing the Beta Limit in DIII-D Advanced Tokamak Discharges*

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Results are presented from comparisons of modeling and experiment in studies to assess the best choice of discharge shape, q profile and pressure profile for high beta, steady-state, advanced tokamak operation. This is motivated by the need for high $q_{min}\beta_N$ to maximize the self-driven bootstrap current while maintaining high toroidal beta to increase fusion gain, and the requirement that the current profile and pressure profile be self-consistent in steady-state, 100% noninductive discharges. Experiment and theory both show that increases in the achievable normalized beta (β_N) can be obtained through broadening of the pressure profile (Figs. 1−3) and use of symmetric double-null divertor shape (Fig. 4). With broad pressure $\beta_N = 4$ is obtained with the minimum q value (q_{min}) near 2 and $q_{min}\beta_N$ increases with q_{min}. Modeling of equilibria with near 100% bootstrap current indicates that operation with $\beta_N \approx 5$ should be possible with a sufficiently broad pressure profile. The experimental β_N values are well above the no-wall limit. As a result, the plasma response can amplify asymmetric fields causing increased toroidal drag and steepening of the rotation profile. This tends to produce internal barrier-like conditions in which pressure peaking can increase.

Optimization of $q_{min}\beta_N$ is a key to improving the prospects for steady-state advanced tokamak discharges. Steady-state operation requires 100% of the plasma current to be driven noninductively which is best achieved with a high bootstrap current fraction, $f_{BS} \propto \beta_P \propto q\beta_N$, motivating elevated q values across the entire profile. The advanced tokamak scenarios under study at DIII-D have $1.5 < q_{min} < 3$, $q_{95} \approx 5$. The requirement of high fusion gain ($\propto \beta\tau_E \propto \beta_N H_{89}/q_{95}^2$) means that $q\beta_N$ should be optimized by increasing q_{min} rather than q_{95} and that a high value of the β_N limit with wall stabilization is needed. Present DIII-D high performance, high noninductive current fraction discharges operate with β_N = 3.2 to 3.5,

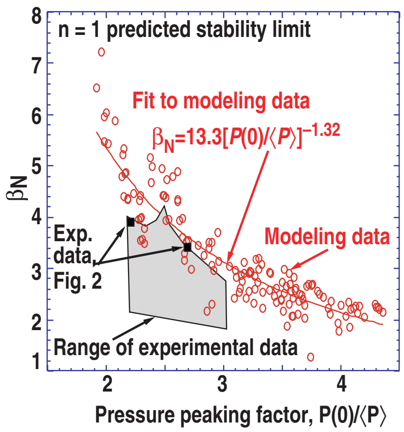

Fig. 1. Calculated ideal n = 1 stability limit as a function of pressure peaking (circles). The scatter in points is a result of variation of discharge shape. The squares are the measured values for the discharges in Fig. 2.

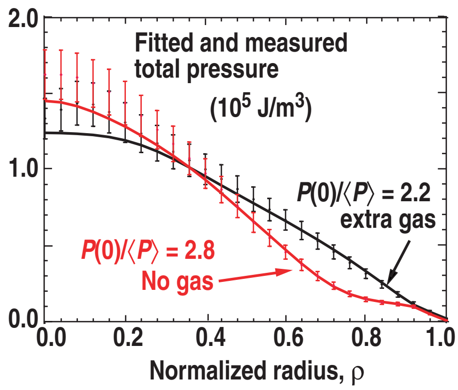

Fig. 2. Measured pressure profiles for discharges with and without extra gas puff to broaden the density and pressure profiles.

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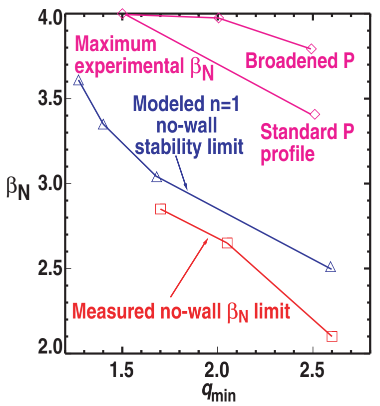

Fig. 3. Experimental and theoretical scaling of β_N with the minimum value of q.

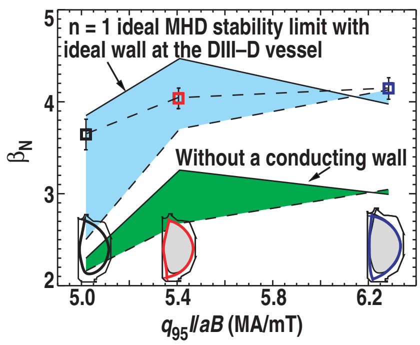

Fig. 4. Measured (squares) β_N for three discharges with varying shape. Higher values of q_{95} I/aB have stronger shaping. Shaded areas show the calculated ideal n=1 limit where the shading represents the profile measurement uncertainties.

$q_{min} \approx 1.5$. Optimization of beta limits would allow operation at $q_{min} \approx 2.5$, $\beta_N > 4$ where f_{BS} would be significantly improved.

Beta limits are predicted to increase strongly as the pressure profile is broadened. This is found in a study of the low toroidal mode number (n) stability of model equilibria as shown in Fig. 1 for n=1. The stability limit was tested for a wide range in discharge shape. Normalized beta limits above 6 for n=1 and near 5 for n=2 are predicted for optimum DIII-D discharge shape (e.g. $\kappa = 2.1$, $\delta = 0.8$) and pressure profile peaking factor $P(0)/\langle P\rangle < 2.3$. The maximum β_N values in the database of steady-state scenario discharges agree with the predicted trend (Fig. 1).

This predicted increase in β_N limit with pressure profile width is observed in the experiment. The pressure profile was broadened (Fig. 2) by using additional gas puffing to broaden the density profile. $P(0)/\langle P\rangle$ decreased from 2.8 to 2.2 and the maximum β_N increased from 3.4 to 4. The β_N limiting instability changed from a disruption due to an n=1 resistive wall mode to a non-disrupting tearing-type mode. As shown in Fig. 1, the tearing mode limited case is predicted to still be significantly below the ideal wall limit.

Reduction in toroidal rotation, a consequence of drag by asymmetric fields which are amplified above the no-wall β limit, is a key indicator of the modified beta limit. In the discharge with stronger pressure peaking there are two large decreases in toroidal rotation: as β_N reaches the no-wall limit and when β_N nears 3.4, the peak value. With the broader pressure profile, there is no strong rotation decrease until $\beta_N \approx 4$. In both cases, as β_N nears its peak value the pressure becomes more peaked. This correlates with a reduction in rotation to near zero in the discharge outer half and increased rotation shear near mid-radius which can modify the energy transport profile.

With broader pressure profiles, the achievable β_N value with $q_{min} \approx 2.5$ is close to that achieved with $q_{min} \approx 1.5$ (Fig. 3). The trend is still for the maximum achievable β_N to decrease somewhat with q_{min}, similar to the measured and calculated no-wall limits (Fig. 3). However, with pressure profile broadening by gas puffing, $q_{min}\beta_N$ increases with q_{min}, offering the prospect of an optimized steady-state, high f_{BS} operating regime.

The achievable β_N value is further increased through choice of discharge shape, particularly by use of an up/down balanced double-null divertor. This contrasts with the single-null divertor shape presently used with the available divertor cryopumps to reduce density in order to increase the EC-driven current. In the experiment, the standard single-null shape was compared to two others that maximized triangularity (δ), elongation (κ) and up/down symmetry. The result was an increase in the maximum β_N from 3.6 to 4.1, in agreement with theory (Fig. 4). A measurement of the no-wall β_N limit also showed an increase through a change from single to double-null divertor. An extensive modeling study of low-n stability limit dependence on κ, δ and squareness is in agreement with the experimental results. The correct choice of squareness for a given κ, δ was found to be important.

Experiment and modeling are also pointing to a possible alternate steady-state scenario with a relatively flat q profile, $q_{95} - q_{min} < 1$. A modeling study of an equilibrium with $q_{95} \approx 3$ and $q_{min} \approx 2$ has predicted an ideal wall β_N limit of $13\ell_i \approx 6.5$. Experiments have shown promise, with maximum $\beta_N \approx 4$ thus far.