Demonstration in the DIII–D Tokamak of an Alternate Baseline Scenario for ITER and Other Burning Plasma Experiments*

T.C. Luce,[1] E.J. Doyle,[2] J.R. Ferron,[1] A.W. Hyatt,[1] A.G. Kellman,[1] R.J. La Haye,[1] C.J. Lasnier,[3] M. Murakami,[4] P.A. Politzer,[1] J.T. Scoville,[1] M.R. Wade,[4] J.G. Watkins[5]

[1]General Atomics, P.O. Box 85608, San Diego, California, 92186-5608 USA
email: luce@fusion.gat.com
[2]University of California, Los Angeles, California 90095-1597 USA
[3]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551 USA
[4]Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37831 USA
[5]Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185

One of the most significant engineering challenges for the designer of a tokamak fusion power plant is the possibility of a sudden termination of the plasma current. Currents induced in the plant core can lead to destructive forces, and runaway electrons generated by the plasma current collapse may damage the vacuum vessel. Present design methods assume that the probability of a disruption increases with current at fixed magnetic field and size. Because fusion performance is assumed to scale in a similar manner, reactor designs seek a compromise between increased fusion performance and reduced susceptibility to disruptions, generally resulting in a design with q_{95} ~ 3.0. Discharges developed in the DIII–D tokamak challenge this notion, having demonstrated q_{95} can be increased by 30% with only a modest reduction in fusion performance. The higher q_{95} translates directly into lower disruption forces, while the modest change in fusion performance challenges the basic design rules for burning plasma experiments. These ELMing H–mode discharges have been run to stationary conditions on the resistive time scale (> 6 s), and involve feedback control only of global quantities rather than profiles. This level of performance has been reproducibly obtained in operational campaigns spanning the past three years.

Discharges reaching a normalized fusion performance ($\beta_N H_{89}$) of 8.5 have been achieved in the DIII–D tokamak for ~4 energy confinement times (τ_E), Fig. 1. Longer duration discharges (~35 τ_E) have stationary current profiles at $\beta_N H_{89}$ ~7. Both discharges are terminated by a hardware limitation, not by evolution of the discharge or plasma instabilities. For comparison, a discharge in conventional low-q ELMing H–mode operational scenario is shown. This discharge has $\beta_N H_{89}$ ~5 for ~ 4 τ_E, but is terminated by a disruption caused by a rotating m=2/n=1 tearing mode which locked. Steady operation at low q may require lower normalized performance. The no-wall ideal β limit is expected to be near β_N = 3.5 in each

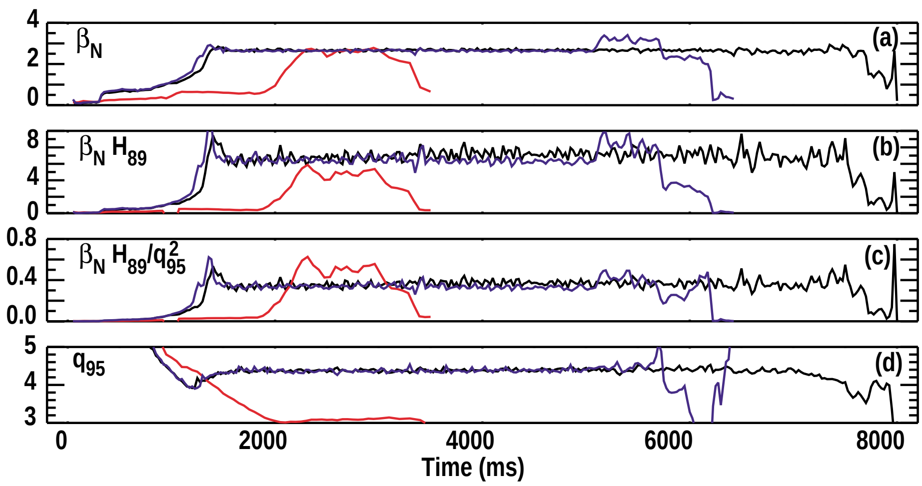

Fig. 1. Comparison of (a) normalized β (β_N), (b) normalized performance ($\beta_N H_{89}$), (c) the ignition figure of merit $\left(\beta_N H_{89} / q_{95}^2\right)$, and (d) the q_{95} in a conventional, low q discharge with two discharges at q_{95} ~ 4.5.

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case. The nominal ITER operating point has β_N = 1.8, $\beta_N H_{89}$ = 3.6, $\beta_N H_{89} / q_{95}^2$ = 0.4, and q_{95} = 3.0. The present discharges at higher q_{95} have the ignition figure of merit at or above the nominal ITER level.

The key to the high fusion performance relative to that expected for conventional ELMing H–mode in this type of discharge appears to be reaching a stationary current profile with q_{min} > 1. Significant heating power by neutral beam injection (NBI) is applied during the current ramp. The plasma is constrained to remain in L–mode during this phase by operating with the X–point opposite the ∇B drift direction. The NBI power is controlled to yield a current profile at flattop which has q_{min} > 1 but without an internal transport barrier. An L-H transition is induced just after current flattop by transiently changing the shape to a symmetric double-null. After the transition, the shape is returned to a slightly unbalanced double-null, in order to control the plasma density using the two cryopumps in the top of the vessel. The stored energy is held constant by feedback control of the NBI power. After ~2 s, the pitch angle signals from the motional Stark effect (MSE) diagnostic reach a stationary state, indicating the current profile is no longer evolving. This is consistent with the estimated current profile relaxation time of 1.8 s for $\langle T_e \rangle$ = 2 keV. Reconstructions of the magnetic equilibrium using the MSE data indicate that the profile of the safety factor (q) is monotonic and has $q(0)$ ~ 1.05. No sawtooth or fishbone instabilities are observed.

Equilibration of the current profile with q_{min} > 1 is unexpected on the basis of simulations of the current diffusion using the measured kinetic profiles and neoclassical Ohm's law. However, analysis of the internal loop voltage through time histories of magnetic reconstructions indicates an apparent voltage source of ~10 mV at the location of an m=3/n=2 tearing mode. This small non-inductive voltage source appears to be essential to obtaining a current profile with q_{min} > 1. The reduction in confinement due to this mode is relatively small (~10%) and the confinement quality remains good (H_{89}p ~ 2.5).

The global particle balance indicates that the walls are playing no role in setting the level of particle density. The density is feedback controlled by means of gas puffing. Any gas not taken up by the plasma is exhausted to the pumps, indicating the walls are neither a source or sink of particles. Because the wall time constant is potentially the largest physical time constant affecting the plasma performance, the equilibration of the wall is an important aspect of stationarity for these discharges.

To project these discharges to burning plasmas, it is assumed that the usual parametric dependencies of confinement hold. To maintain the same fusion gain, the value of $\left(\beta_N H_{89} / q_{95}^2\right)$ must remain constant, compared to the standard ELMing H–mode scenario. In the best cases, $\left(\beta_N H_{89} / q_{95}^2\right)$ remains about 10% smaller than a low q ELMing H–mode. Another factor is that $T_i > T_e$. It will be necessary to demonstrate similar confinement quality with $T_e = T_i$ to qualify this as a burning plasma scenario. Finally, the bootstrap current fraction is <50% in these discharges due to the low value of q_{min}. It is unlikely that these discharges represent a path to full non-inductive operation at high fusion gain.

The main advantage of such a scenario lies in the reduction in plasma current. Depending on the type of disruption, the forces on the vessel and support structure should be reduced by 30%–50%. The knock-on avalanche process is exponential in plasma current; therefore, this process should be completely negligible compared to a full current discharge. Disruptions are a concern for the low-q scenario; the example discharge shown in Fig. 1 has an m=2/n=1 tearing mode which locks and disrupts the plasma. No attempt was made to optimize the low-q discharge, but this may indicate that the level of performance shown can not be sustained without active stabilization of the tearing modes. In addition to improved tolerance to disruptions, it is believed that effects of ELMs on the divertor may be reduced. Additional experiments are required to verify this.

In conclusion, a stationary scenario with significant benefits for a burning plasma experiment has been demonstrated in the DIII–D tokamak. Normalized performance ($\beta_N H_{89}$) has reached 7.0 for 35 τ_E and 8.5 for 4 τ_E, both limited by hardware. This level of performance approaches that of the standard low-q ELMing H–mode scenario envisioned for ITER and other burning plasma experiments. The advance in normalized performance is due both to higher β_N and higher H_{89} than that anticipated for low-q ELMing H–mode.