

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

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Abstract. Discharges which can satisfy the high gain goals of burning plasma experiments have been demonstrated in the DIII-D tokamak in stationary conditions with relatively low plasma current ($q_{95} > 4$). A figure of merit for fusion gain $\beta_N H_{89} / q_{95}^2$ has been maintained at values corresponding to $Q = 10$ operation in a burning plasma for > 6 s or $36 \tau_E$ and $2 \tau_R$. The key element is the relaxation of the current profile to a stationary state with $q_{\min} > 1$, which allows stable operation up to the no-wall ideal β limit. These plasmas maintain particle balance by active pumping rather than transient wall conditioning. The reduced current lessens significantly the potential for structural damage in the event of a major disruption.

1. Introduction

The conventional design approach to a burning plasma in a tokamak has high plasma current and an H-mode edge with edge localized modes (ELMs) [1]. Because the β limit, the density limit, and the energy confinement all scale linearly with plasma current, the fusion power and gain increase with plasma current. The principal constraint on the magnitude of the plasma current is the risk of a major disruption. The potential for damage to the mechanical structure by electromagnetic forces and to the plasma-facing components due to a rapid deposition of the stored energy in the plasma is significant. The compromise between the increase in fusion performance and the potential for damage as the plasma current is increased is typically struck at $q_{95} \approx 3$.

Discharges developed in the DIII-D tokamak offer an alternate solution which would achieve many of the performance goals of burning plasma experiments. These discharges project to similar fusion gain at lower plasma current for the same size and toroidal magnetic field. The lower plasma current both reduces the potential for damage in the case of disruption and lengthens the possible discharge duration through reduced flux consumption. These discharges have been operated in the DIII-D tokamak under stationary conditions where the pressure profile, the current profile, and the wall particle balance are all in equilibrium. The discharges have only $\sim 50\%$ noninductive current so they are not true steady state.

2. Development of Stationary Discharges in DIII-D

The key element to achieving high fusion gain conditions is a stationary current profile with $q_{\min} > 1$. In addition, active control of particle and energy content of the plasma implies an excellent degree of reproducibility, in addition to stationary conditions. A representative discharge of this type is shown in Fig. 1. The discharge is formed limited on the inside wall and then diverted at 300 ms to form a double-null plasma. The plasma is biased vertically upward so that the top null is dominant. This increases the L-H threshold power and engages the upper cryopumps to control the particle inventory. Two neutral beams are injected at 300 ms to slow the evolution of the plasma current density. The q profile is monotonic at these early times, but nearly flat past normalized radius $\rho = 0.6$. Additional neutral beam power is added at 800 ms to further slow the current evolution. The current profile at the end of the current ramp is hollow yielding a q profile with a shallow minimum near $\rho = 0.6$.

The two important elements of the current ramp phase are maintaining an L-mode edge and controlling the wall particle inventory by pumping. The L-mode edge maintains high internal inductance (ℓ_i) which is important since the achievable β in discharges with monotonic q

profiles in DIII-D is found to be proportional to ℓ_i [2]. A reduction in upward bias and additional neutral beam power at the end of the current ramp result in a reproducible L–H transition at 1200 ms. The target density has been adjusted to give a short ELM-free period, so that the density in the H-mode phase does not overshoot the desired value.

The ELM-free phase transitions smoothly into a steady ELMy edge [Fig. 1(c)]. The ELMs provide both density and impurity regulation in the stationary phase [Fig. 1(f)]. The contribution to Z_{eff} from carbon, determined from active charge exchange spectroscopy, is about 1.6 in the core and is not increasing. Carbon is expected to be the dominant impurity and no significant metallic impurities are observed. The density is under feedback control using gas puffing and active pumping.

The plasma energy content is also under feedback control [Fig. 1(d)]. The neutral beams [Fig. 1(a)] are controlled to maintain a constant level of diamagnetic flux. The requested $\beta_N = 2.7$ is about 85% of the expected no-wall β limit for these discharges, as estimated by $4\ell_i$ [Fig. 1(d)]. A low level of magnetic fluctuations is seen throughout the stationary phase of the discharge [Fig. 1(b)]. After 3000 ms, the dominant mode is a 3/2 tearing mode. Note that the maximum mode amplitude at the wall is ~ 3 G, which corresponds to an island with ~ 4 cm half-width in the plasma. No sawtooth or fishbone activity is measured, consistent with a current profile that relaxes to a stationary value with $q_{\text{min}} > 1$.

These discharges are in equilibrium with respect to the pressure profile, the current profile, and the wall particle inventory. The pressure profile remains constant for ~ 36 global energy confinement times (τ_E) while the current profile is stationary for ~ 2 current redistribution times (τ_R). This stationary phase is remarkable because of the high level of performance. As mentioned above, $\beta_N = 2.7$ or $\sim 85\%$ of the expected no-wall β limit. The confinement time compared to the ITER-89P scaling [3] is 2.5. This gives a normalized performance product $\beta_N H_{89} = 6.8$ at $q_{95} = 4.2$. A common figure of merit for fusion gain is $\beta_N H_{89}/q_{95}^2$. The value of $\beta_N H_{89}/q_{95}^2$ achieved in steady conditions is 0.39. The present ITER-FEAT reference scenario [4] has the possibility of $Q = 10$ operation at $\beta_N = 1.8$, $H_{89} = 2.1$, $q_{95} = 3.0$ giving $\beta_N H_{89}/q_{95}^2 = 0.42$. Since the fusion gain would be comparable at 30% lower current (with corresponding reductions in the impact of a major disruption as discussed in the introduction), the type of discharges discussed here warrants investigation as an alternative means to achieve the fusion gain objectives in a burning plasma experiment. In addition, the high gain at lower current may substantially enhance the technology phase of a burning plasma experiment where increased pulse length (fluence) is important.

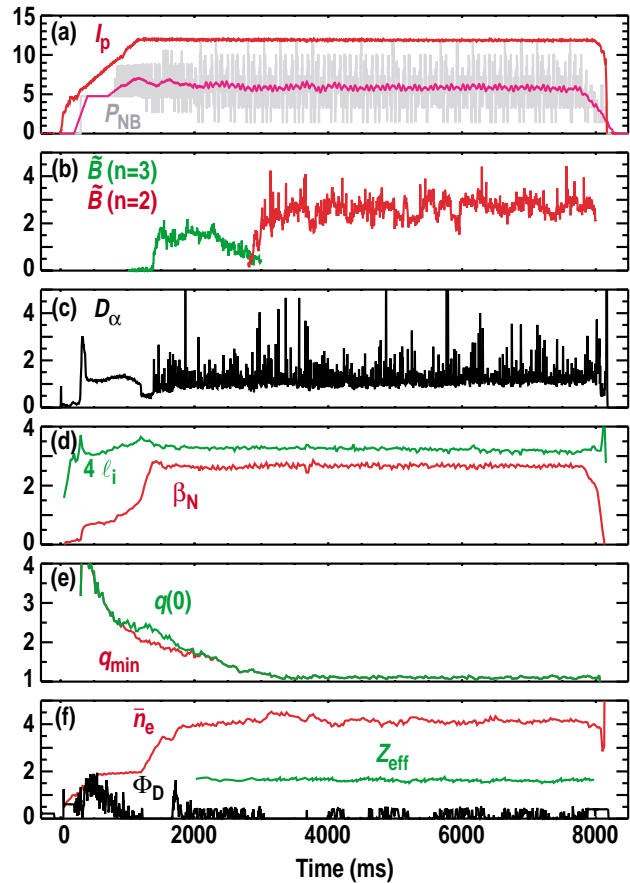


Fig. 1. Time histories of various plasma parameters for a typical long-pulse stationary discharge ($B_T = 1.7$ T). (a) 10x plasma current I_p (MA), neutral beam power P_{NB} (MW), P_{NB} with a 200 ms moving average (MW), (b) magnetic perturbations measured at the vacuum vessel (G), (c) D_α emission from the upper divertor (10^{15} photons/cm²/s), (d) normalized β (β_N) (%-MA/m-T) and $4\times$ internal inductance (ℓ_i), (e) q_{min} and $q(0)$, (f) line-averaged density \bar{n}_e (10^{19} m⁻³), Z_{eff} from carbon, gas flow $\Phi_D/100$ (not including neutral beam sources) (torr· ℓ /s).

3. Current Density Profile Evolution and Stability

A direct method to show that the current profile has become stationary is to examine the magnetic pitch angles measured inside the plasma by motional Stark effect (MSE) spectroscopy [5]. The data from the tangential viewing array are shown in Fig. 2. From ~ 4000 ms until the neutral beam power drops at 7800 ms, the measured pitch angles are constant within the measurement uncertainties. This implies that the electric field is constant from $R = 1.5$ – 2.1 m. Other MSE views indicate the electric field is constant out to the radius where the ELMs have a substantial effect and even there the field is constant in a time-average sense. The time scale on which the current profile equilibrates is consistent with expectations of the redistribution time using neoclassical resistivity. The characteristic time [6] is evaluated using neoclassical conductivity [7] and the real plasma cross-sectional area. For these discharges, $\tau_R = 2$ s.

Equilibrium reconstructions including the MSE data show $q_{min} > 1$ [Fig. 1(e)]. The expected equilibrium current profile would have $q_{min} < 1$. No high-frequency magnetic perturbations are detected which would indicate a redistribution of the fast ion population and a broadening of the neutral beam current drive. Analysis of the internal loop voltage [8] indicates a voltage source at the location of the $3/2$ tearing mode [9]. It is speculated that this small voltage source at $\rho = 0.5$ is sufficient to broaden the current profile to allow q_{min} to remain above 1.

Even though the plasma is unstable to $n=3$ and $n=2$ tearing modes, these are not a limit to the plasma pressure. Initial studies [10] found that the $2/1$ tearing mode limited the pressure. If the β was increased from the outset of the feedback controlled phase, the β_N was limited to < 2.9 . This β limit is typically not a disruptive limit, although the full beam torque probably prevents the mode from locking to the wall, which is the normal prerequisite to a disruption.

Subsequent experiments have demonstrated that higher β operation is possible, up to the expected no-wall limit ($4\ell_i$), if the increase in β occurs after the current has reached its stationary state. An example of a step increase in β is shown in Fig. 3. The requested β_N is raised to 3.2 and held for 600 ms until a power supply fault ends the discharge. The energy confinement improves ($H_{89} = 2.8$) giving $\beta_N H_{89} = 8.9$ and $\beta_N H_{89} / q_{95}^2 = 0.44$. If the requested β_N is raised

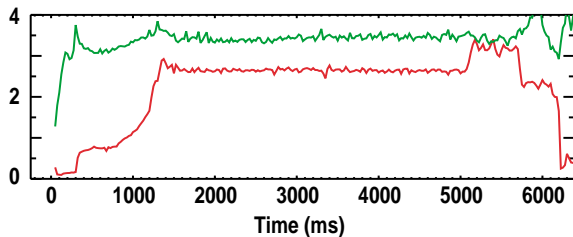


Fig. 3. Time histories of β_N (red) and $4 \times$ internal inductance (green) ($4 \ell_i$) for a case where the requested β has a step increase to $\beta_N = 3.2$ at 5000 ms ($B_T = 1.7$ T, $I_p = 1.2$ MA).

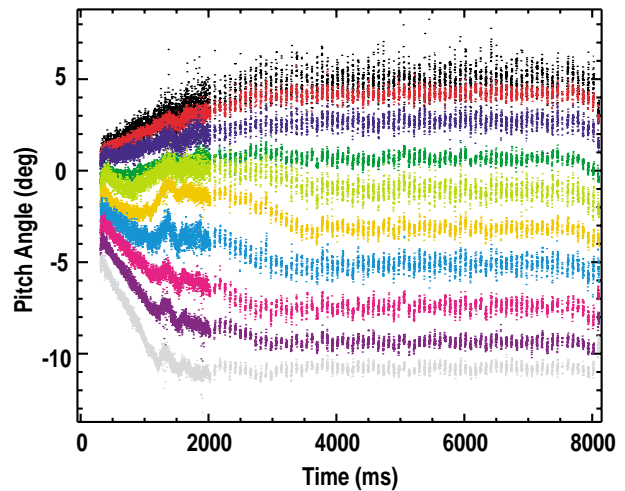


Fig. 2. Time history of magnetic pitch angles (deg) from the discharge shown in Fig. 1 measured by the tangential viewing MSE system ($R = 1.5$ – 2.1 m). Each color represents a separate channel. The probe beam is run continuously until 2000 ms, then modulated to allow measurements throughout the discharge.

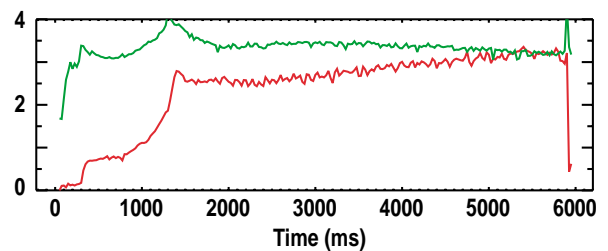


Fig. 4. Time histories of β_N (red) and $4 \times$ internal inductance (green) ($4 \ell_i$) for a case where the requested β is slowly ramped to $\beta_N = 3.2$ at 5000 ms ($B_T = 1.7$ T, $I_p = 1.2$ MA).

further to well above $4\ell_i$, a 2/1 tearing mode appears. This is consistent with recent theoretical studies which indicate that a tearing mode can be destabilized when the classical tearing stability index Δ' becomes positive as an ideal MHD limit is approached [11]. The β can also be raised gradually as shown in Fig. 4. Once the current profile has been established, the β request was smoothly increased starting at 2300 ms up to $\beta_N = 3.2$ at 5400 ms. The β_N corresponds to the expected no-wall β limit, as estimated by $4\ell_i$. This discharge ends due to a programmed termination of the neutral beams. Enhanced stability to tearing modes in the absence of sawteeth has been observed previously in DIII-D [12]. A fiducial discharge with similar shape and field operated with $q_{95} = 3.1$ was unstable at $\beta_N = 2.8$ to the 2/1 tearing mode, which locked and disrupted the plasma. This is consistent with the previous DIII-D experience [12] and the ITER design rules which recommend limiting β_N well below 2.5 to avoid the tearing modes.

4. Particle and Energy Balance

The wall plays little role in the particle balance during the stationary phase of these discharges. The various components of the particle balance are shown in Fig. 5. After the L-H transition at 1200 ms, the wall plays an insignificant role in the particle balance. The wall is very slowly returning the particles it accumulated during the L-mode current ramp. The control obtained over the particle inventory in the plasma is maintained by active feedback and pumping rather than preconditioning of the walls. Previously reported discharges showed almost no change in the wall inventory over the 5 s stationary phase [9].

The energy confinement in these discharges compared to the ITER-89P scaling relation [3] improves with increasing β_N . This is consistent with the observation that most scaling relations have a degradation in confinement with increasing β , while dedicated experiments do not see this degradation [13]. It may be surprising that confinement enhancement of up to $H_{89} = 2.8$ can be obtained with a saturated 3/2 tearing mode. However, estimates of the reduction in stored energy assuming flattening of the pressure profile across the island [14] indicate $<10\%$ reduction in τ_E is expected. In the case of the discharge shown in Fig. 1, the inferred island half-width is only 4 cm. These estimates are confirmed in discharges where the tearing mode onset is late. The power demanded by the feedback system to maintain constant β increases $<10\%$ after the mode is observed.

The energy confinement observed is also consistent with estimates of the transport driven by drift-wave turbulence. The profiles calculated using the GLF23 model [15] compare well with the measured electron and ion temperature profiles. The GLF23 model incorporates turbulent transport from ion temperature gradient modes, trapped electron modes, and electron temperature gradient modes including the effects of $E \times B$ shear stabilization of long wavelength modes. The $E \times B$ shear has a modest effect in these calculations. The transport is reduced from the transport calculated in the absence of $E \times B$ shear; however, the effective diffusivity remains well above the neoclassical level, indicating the $E \times B$ shear does not fully stabilize the turbulence.

5. Discussion and Conclusions

The range over which the density, magnetic field, and plasma current have been varied is fairly small at present. However, this has

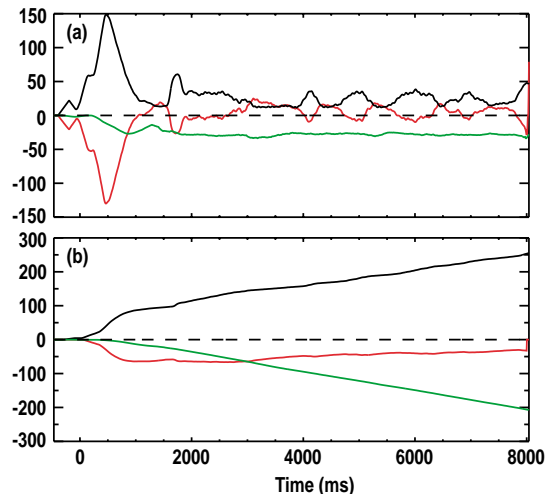


Fig. 5. Time histories of quantities relevant to the particle balance for the discharge shown in Fig. 1. (a) total gas injection and NB injection rates (black) ($\text{torr}\cdot\ell/\text{s}$), total removal rates for the inner and outer divertor cryopumps (green) ($\text{torr}\cdot\ell/\text{s}$) and wall rate (red) ($\text{torr}\cdot\ell/\text{s}$). The sign convention is that positive rates indicate a source of particles to the plasma. (b) Integrated sources ($\text{torr}\cdot\ell$) from the gas injectors and neutral beams (black), divertor cryopumps (green), and the wall (red).

been by design; in no instance was the variation limited due to the loss of the performance. The key element from which all of the positive aspects seem to flow is the stationary current profile with $q_{\min} > 1$. The present understanding indicates that the small tearing mode at the $q = 1.5$ surface plays an essential role in the final state achieved. Without a physics model for the apparent dynamo action, it is unclear how this will extrapolate to any other device. The enhanced stability appears to follow from the avoidance of sawteeth. Experiments are needed with counter fast wave current drive on-axis or co-ECCD off-axis to see if such current profiles can be maintained without the tearing mode.

It may be possible to extend operations into the region between the no-wall β limit and the ideal-wall β limit. These discharges are rotating sufficiently fast that the DIII-D wall should provide significant stabilization. No indication of a resistive wall mode has been found as β is increased. In every case, a 2/1 tearing mode occurs when the β rises above the estimated no-wall β limit. Recent experiments have demonstrated complete suppression of the 2/1 tearing mode at low β . No attempt has been made to increase β during suppression. It is important to recall that performance corresponding to $Q = 10$ in ITER has been maintained without going above the no-wall limit.

The main question with respect to extrapolation of the confinement to a burning plasma is the role of T_i/T_e in achieving good confinement. At present, T_i/T_e is everywhere >1 , which has been shown to be favorable for confinement [16] and is expected to be stabilizing to drift-wave turbulence. Limited scans of density indicate that the reduction of confinement as $T_i/T_e \rightarrow 1$ may be modest. As the central T_i/T_e varies from 1.9 to 1.5, the thermal confinement drops by $<10\%$. It appears that nominal ITER values of collisionality and $T_i/T_e = 1$ can be obtained with n/n_{GW} about 0.7 in DIII-D.

In summary, a new stationary mode of operation has been discovered in DIII-D which has exciting prospects for high gain demonstrations in burning plasma experiments. The pressure profile is stationary for up to $36 \tau_E$ and the current profile is stationary to $>2 \tau_R$. Active particle control is used rather than conditioning of the wall which can only manipulate the particle balance transiently. Stationary performance of $\beta_N = 2.7$, $\beta_{NH89} \sim 7$, and $\beta_{NH89}/q_{95}^2 = 0.39$ have been demonstrated. Discharges have been operated with $\beta_{NH89} \sim 9$ and $\beta_{NH89}/q_{95} = 0.44$ for ~ 1 s near the estimated no-wall β limit. The key to accessing this high performance regime appears to be reaching high β before q_{\min} reaches 1 and sawteeth begin. Under the influence of a small 3/2 tearing mode, the current profile relaxes to a stationary state with $q_{\min} \geq 1$. Assuming a basis for extrapolating these discharges to a burning plasma experiment can be established, they represent a scenario by which the high gain goals of a burning plasma experiment could be achieved with reduced potential for damage in a disruption and longer pulse length. These discharges could also play a significant role in a technology testing phase where high gain at high duty cycle is important.

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