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Sustained High Beta Plasmas with Negative Central Shear in DIII-D

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Abstract. Simultaneous ramping of the plasma current and toroidal field, and application of early neutral beam heating in DIII–D have produced current-hole type discharges sustained for ~2 s at high values of normalized pressure (β_N ~ 4) and safety factor (q_{min} ~ 2). The combination of internal transport barrier and negative central magnetic shear results in high energy confinement (H_{89} > 2.5) and good bootstrap current alignment (f_{BS} ~ 60%). Previously, stability limits in plasmas with core transport barriers have been observed at moderate values of β_N (<3) because of characteristically high pressure-peaking. A noninductive current fraction of ~90% has been observed at plasma β ~ 5% in these DIII-D experiments. Stability modeling shows the possibility for operation up to β ~ 6%, suggesting a possible path to high fusion performance, steady-state tokamak scenarios with a large fraction of bootstrap current.

A first step to demonstration of ~100% bootstrap fraction Advanced Tokamak (AT) operation is achieving and sustaining high normalized β (β_N > 5) for at least one current relaxation time in plasmas with a q-profile having high q_{min} (≥2) for high bootstrap current fraction, high radius of q_{min} [$\rho(q_{min}) \geq 0.8$] for good bootstrap alignment, and low q_{95} for high fusion gain. Until recently, the best experimental results toward this goal have been limited to β_N < 4 (~3.5) and q_{min} < 2 (~1.5) by ideal or resistive magnetohydrodynamic (MHD) instabilities [1]. Systematic stability studies [2] have found that high-β_N AT discharges in DIII-D exceed the no-wall β_N limits and approach the ideal-wall limits, which at q_{min} > 2 are lower than at q_{min} < 2. Proximity to the ideal wall limit can destabilize tearing modes. Furthermore, resistive wall mode (RWM) rotation thresholds are predicted to be high at q_{min} > 2. Encouragingly, modeling and experimental results [1–3] have shown that plasma discharges with a broader pressure profile have higher ideal-wall instability β_N thresholds. In these previous experiments the pressure profile was broadened by gas puffing to increase the edge density, and β_N ~ 4 at q_{min} ~ 2 was reached, although only transiently.

A new experimental approach to sustaining high β at high q_{min} is based on the hypothesis that a broad pressure profile may be obtained more easily by creating a broad q-profile. This approach has led to the generation in DIII-D of discharges with very strong negative central magnetic shear (NCS), internal transport barriers (ITBs), and broad pressure profiles, capable of sustaining high β and high energy confinement with $\beta_N \sim 4$, $\beta_T \sim 3\%$-7% and $H_{89} \sim 2.5$ for ~2 seconds. The minimum safety factor q_{min} was maintained at ~2, transiently leading to high bootstrap current fraction operation, $f_{BS} \sim 60\%$ with noninductive current fraction, f_{NI} of up to 90%. These results address a critical issue for ITB operation in AT plasmas, obtaining sustained ITB profiles compatible with high β limits, and suggest a possible path to high fusion performance, steady-state tokamak scenarios with a large fraction of bootstrap current.

In these DIII-D experiments the safety factor near the plasma boundary, q_{95}, is lowered by simultaneously ramping down the toroidal field and ramping up the plasma current. If the ramps take place while the plasma core is sufficiently hot, the value of q_{min} remains insensitive to the changes in $\mathrm{B_T}$ and $\mathrm{I_P}$, therefore the overall q-profile becomes broader. These ramps also have the effect that the plasmas are non-stationary with evolving q-profiles, even though β_N is maintained ~constant using feedback control of the neutral beam injection (NBI) power.

High values of normalized pressure ($\beta_N \sim 4$) and safety factor ($q_{min} \sim 2$) have been sustained simultaneously for ~2 s, as shown in Fig. 1. The plasma density in these discharges is typically ~0.5 of the Greenwald density, and electron cyclotron current drive (ECCD) at minor radius $\rho \sim 0.55$ is utilized to help sustain $q_{min} \sim 2$. The combination of internal transport barrier and negative central magnetic shear results in high confinement ($H_{89} > 2.5$) and, with safety factor $q_{95} \sim 5.5$-3.5, also leads to high normalized fusion performance, with fusion gain factor $G = (\beta_N H_{89})/q_{95}^2$ ranging from 0.3 to 0.8 and spanning the anticipated International Thermonuclear Experimental Reactor (ITER) performance range. Generally, the high performance is terminated by an (m,n)=(2,1) tearing mode destabilized as q_{min} approaches 1.5.

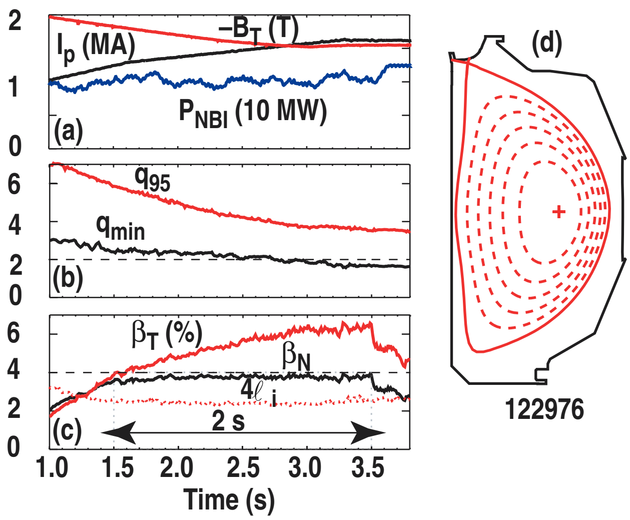

Fig. 1. Time evolution of parameters for a DIII-D discharge sustained for about two seconds at high values of (b) the minimum safety factor, q_{min}, and (c) the normalized pressure, β_N and β_T. Also shown in (a) are the plasma current, toroidal field, and neutral beam injected power, in (b) the edge safety factor, q_{95}, in (*c) an estimate of the no-wall β_N limit, $4\ell_i$, and in (d) the cross sections of the plasma and of the DIII-D wall.

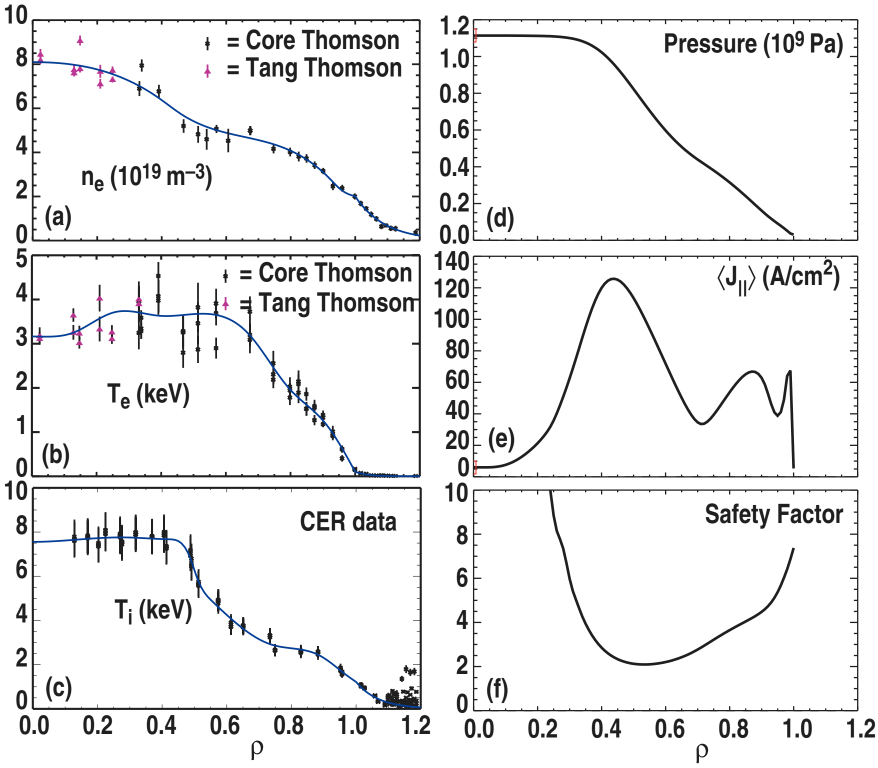

Fig. 2. Radial profile measurements of (a) electron density, (b) electron temperature and (c) ion temperature, and kinetic reconstructions of the profiles of the (d) total pressure, (e) current density, and (f) safety factor, for a discharge similar to that of Fig. 1, but with constant plasma current.

Resistive wall mode stabilization is essential to these plasmas which run at β_N values above 6 times the internal inductance ℓ_i. Simultaneous feedback control of both the external and internal sets of n=1 magnetic coils was used to maintain optimal error field correction (so as to maintain high levels of plasma rotation) and direct resistive wall mode stabilization, allowing operation above the free-boundary β-limit.

ITBs are clearly recognized in the ion temperature and rotation profiles at $\rho \sim 0.5$ but not in the electron temperature profile, which is very broad (Fig. 2). The ion temperature and the overall pressure profiles are very flat at $\rho < 0.5$, which indicates extremely large radial transport in this region. One of the reasons known to lead to poor confinement in the central region is the existence of a current hole in the plasma core [4,5], which is also observed in these DIII-D discharges.

Previously, the stability limit in tokamak plasmas with internal transport barriers has been encountered at moderate values of β_N (<3) [6] because of the pressure peaking which normally develops from improved core confinement. Similarly, plasmas with near-hollow current profile and strongly negative central shear have been associated with low β limits. In these DIII-D experiments the pressure peaking remains low, with a pressure peaking factor, $P(0)/\langle P\rangle \sim 2$–$2.5$ (where $\langle P\rangle$ is the volume average pressure). This low pressure peaking is likely due to several factors: large width of the flat portion of the pressure profile in the current hole, very broad electron temperature profile, and redistribution of the fast ions

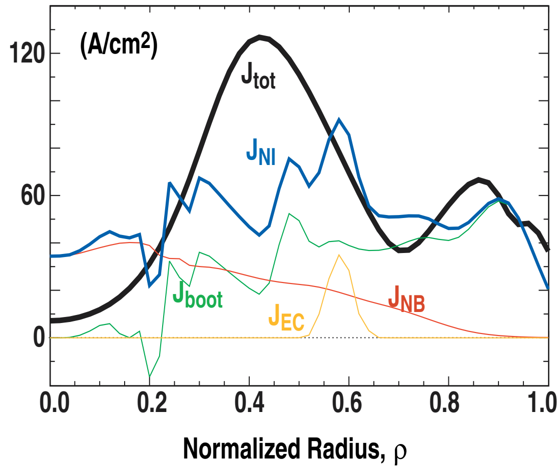

Fig. 3. The ONETWO/NUBEAM calculated current density profiles for the equilibrium reconstruction shown in Fig. 2. Shown are the profiles of the total current density (J_{tot}), noninductive current (J_{NI}), neutral beam driven current (J_{NB}), electron cyclotron driven current (J_{EC}), bootstrap current (J_{boot}).

towards the plasma edge because of large particle orbits at high safety factor in the core. A broad pressure profile is favorable for MHD stability and compensates for the unfavorable effects of a broad current profile: a broad current profile leads to a low no-wall β_N limit ~$4\ell_i$ ~ 2.5. However, the ideal-wall limit for these discharges is calculated to be approximately ~$8\ell_i$ ~ 5. Interestingly, increasing β_N in these plasmas reduces the pressure peaking and consequently increases the ideal-wall β limit. This effect may be caused by a broadening of the current hole with increasing heating power from the neutral beams.

High values of the noninductive currents fraction have been achieved. For the full-kinetic equilibrium reconstruction shown in Fig. 2, a transport analysis by the ONETWO code using the Monte Carlo fast ion physics package, Nubeam [7], shows a fairly well-aligned noninductive current profile, Fig. 3. The calculated noninductive current fraction at the experimental β_N ~ 4 is ~85%, although the internal loop voltage analysis suggests that the noninductive fraction is somewhat higher at the time under consideration. Nevertheless, higher values of the bootstrap fraction are possible with higher β_N. Stability modeling predicts the possibility to increase β_N further, up to the ideal-wall limit at β_N ~ 5, indicating a path to steady-state tokamak operation at high fusion performance and large bootstrap current fraction.

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