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ITER HYBRID SCENARIO RESEARCH ON DIII-D

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ITER Hybrid Scenario Research on DIII–D

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Recent DIII–D research has focused on expanding the operational space of hybrid (q_{95}~4) and Advanced Inductive (AI) (q_{95}~3) operation, and understanding the underlying physics. Hybrid plasmas with reduced plasma rotation produced by counter neutral beam injection show a modest ~20% decrease in confinement quality, and projections for ITER operation indicate Q_{FUS}~10. Hybrids have been obtained in lower single-null (LSN), double-null (DN), and upper single-null (USN) plasma shapes and we have investigated both early- and late-heating scenarios.

I. Characteristics of Hybrid and AI Discharges at Low Rotation

A major thrust of the DIII-D program is the development of a long duration ITER discharge with higher performance than the ITER baseline (H_{98Y2}~1, $\beta_N \ll \beta_{N\text{“no-wall” limit}}$) but lower plasma beta ($\beta_N \sim \beta_{N\text{“no-wall” limit}}$) and bootstrap fraction (f_{BS}~0.3-0.5) than the Advanced Tokamak (AT) regime (H_{98Y2}>1, $\beta_N \sim \beta_{N,\text{“ideal-wall” limit}}$, f_{BS}~0.8). On DIII-D, we have developed the AI (q_{95}~3, f_{BS}~0.3) and hybrid (q_{95}~4, f_{BS}~0.4) regimes with higher β_N than conventional tokamak discharges. Both of these regimes have a broadened, fully relaxed current profile with q_o~1; the AI has small sawteeth, and the hybrid is sawtooth-free. On DIII-D [1,2] a benign m/n=3/2 neoclassical tearing mode (NTM) is associated with the broadened current profile, and results in improved confinement and stability against the more virulent m/n=2/1 NTM [3]. At q_{95}~3.2, we have sustained a fusion performance parameter ($G=\beta_N H_{89P} q_{95}^2$) G=0.7 for over five current relaxation times. This is to be compared with the estimated value of G=0.42 required in ITER for Q_{FUS}=10 operation. In this paper, we present progress in maintaining high performance AI and hybrid operation at low rotation, expected for ITER, and hybrid operation as a function of plasma shape (LSN, DN, and USN).

The conversion of one of the DIII-D neutral beams to “counter” injection (opposite to the direction of the plasma current) has enabled the study of hybrid and AI performance as a function of core rotation. This is particularly relevant to ITER, as it is anticipated that future, larger machines may have lower rotation. As shown in Fig. 1, a DIII-D hybrid plasma is established by early heating and fueling to provide a broad q-profile with q_{min}>1, followed by a high power phase where the β is maintained by feedback control of the neutral beams with the DIII-D control system. A benign m/n=3/2 (sometimes 4/3) NTM is triggered, maintaining q_{min}>1, suppressing sawteeth, and inhibiting the growth of a m/n=2/1 NTM that degrades plasma performance or leads to a disruption. In other DIII-D discharges, these steady-state conditions have been maintained for ~9 s, which corresponds to 9 current relaxation times. For the discharge in Fig. 1, after the hybrid is established during the period from 1.5-3.4 s, the counter neutral beam is introduced, resulting in reduced toroidal torque. The toroidal rotation at most radii decrease, and the Mach number at r/a=0.5 ($M=v_{tor}/c_s$) decreases from M=0.5 to less than 0.1. This case is typical of cases with $q_{95}\geq3.8$, and the confinement parameter G decreases by about 20% [4]. During the low rotation hybrid phase, the n=2 mode amplitude measured by Mirnov probes increases and the frequency decreases. The H_{98Y2} factor decreases slightly during the low rotation period.

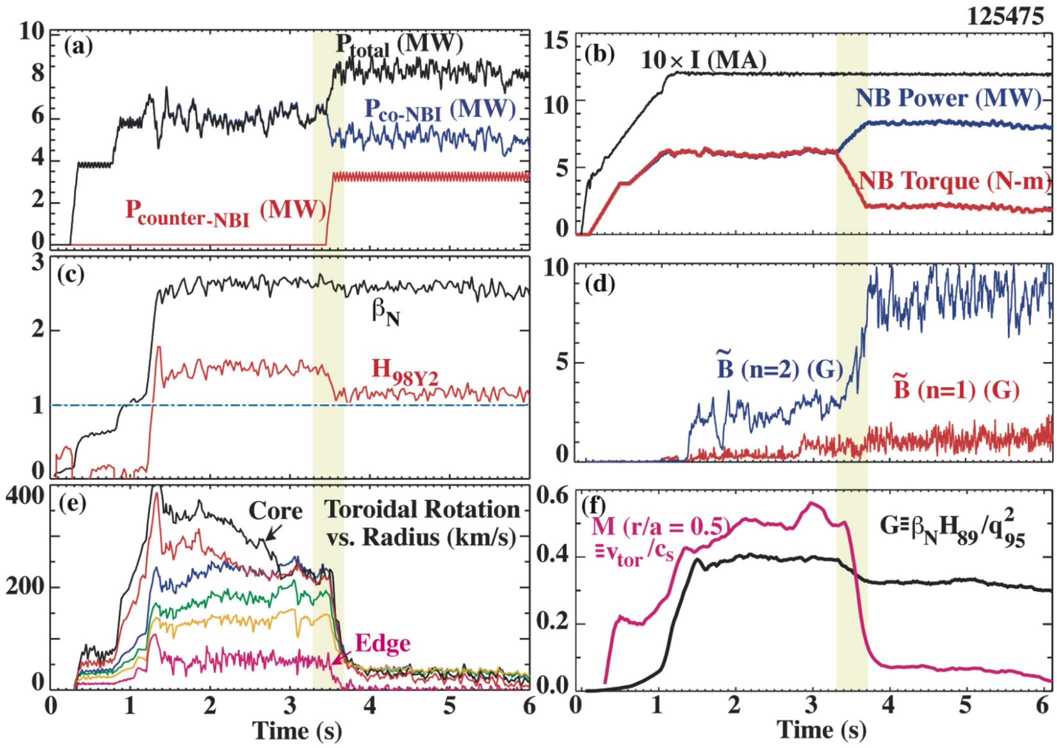

Fig. 1. Hybrid discharge quality {(c) β_N, H_{98Y2}, (f) G} is maintained as core toroidal rotation (e) is decreased from M=0.5 to M~0.1 (f) with counter neutral beam injection (a,b). A slight reduction in H_{98Y2} results in a 20% reduction in G. The benign n=3/2 MHD mode suppresses sawteeth, and increases as the rotation decreases (d).

Counter neutral beam heating has been applied to a q_{95}~3.3 discharge to study AI performance with reduced rotation, as shown in Fig. 2; this case is particularly relevant to projected ITER operation. This AI discharge has a transition to the low rotation phase at the beginning of the high β_N phase, and the central Mach number again decreases by a factor of over four to ~0.1. The high performance phase with G=0.47 is maintained for over 4 s, corresponding to 4 current relaxation times. The dotted line in Fig. 2 shows the G value that would be projected for ITER operation at Q~10. As shown in Fig. 3, as the core Mach number M decreases, the ion χ_i and electron χ_e diffusivities, and the m/n=3/2 amplitude increase, while the energy τ_E, and momentum τ_φ confinement times decrease. Comparisons between experiments and the GLF23 transport model suggest that reduced E×B velocity shear is responsible for the increased core heat transport. Note that even though G is reduced in the low-rotation phase, the ITER projection is $Q_{FUS}\geq10$ for fixed H_{98Y2}.

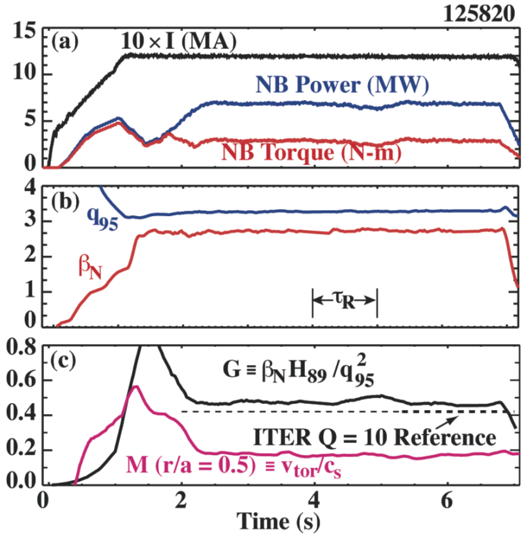

Fig. 2. An AI discharge where the central rotation is decreased with counter injection (a) at about 2 s. (b) The plasma β_N is maintained with neutral beam feedback, and q_{95}~3.3. (c) G is maintained at a level greater than that projected for ITER operation at Q_{FUS}~10 (dotted line).

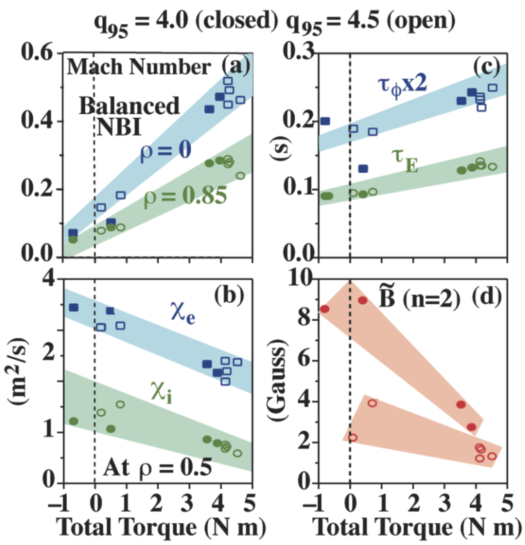

Fig. 3. Counter torque in hybrid discharges decreases: (a) the Mach number, (b) the energy and momentum confinement, and increases: (b) the electron and ion thermal diffusivities, and (d) the m/n=3/2 NTM amplitude. Note the increased NTM amplitude for the q_{95}=4(closed symbols) case.

2. Hybrid Discharge Performance in Upper and Lower Single-Null Divertors

In DIII-D, the normal hybrid sequence is: 1) an USN shape is established to minimize the particle wall inventory, 2) the early heating and fueling profiles are set to provide a broad q-profile with q_{min}>1, 3) the shape is transiently changed to DN, which lowers the H-mode threshold and triggers the H-mode, and 4) the heating is feedback controlled on β by the DIII-D control system so that the benign m/n=3/2 (or 4/3) NTM is triggered, maintaining q_{min}>1. More precisely, the EFIT quantity dRsep, defined to be the distance between the upper and lower separatrices mapped to the plasma midplane, is about 1-2 cm, and is transiently reduced to <0 to trigger the H-mode transition. A negative:zero:positive value of drsep corresponds to a LSN:DN:USN plasma. We then increase dRsep back to its positive USN value for the rest of the discharge.

Recently, we have also produced hybrid discharges with LSN shapes [5], and the confinement scaling factor H_{89P} is shown as a function of dRsep in Fig. 4 for discharges with q_{95}>4. In these discharges, we decrease dRsep to trigger the H-mode transition, and then maintain dRsep at a negative LSN value. LSN hybrids showed reduced rotation compared to the corresponding USN. On DIII-D, the hybrid can be sustained with either an m/n=3/2 (blue) or a 4/3 (red) MHD mode, and these are also denoted in Fig. 4. From this limited dataset, it appears that good hybrid performance can be obtained in both USN and LSN plasmas, but for USN the m/n=4/3 hybrids have improved confinement over m/n=3/2 hybrids due to a higher plasma rotation. The USN shape is also more susceptible to the m/n=2/1 NTM, which can be more readily avoided in LSN plasmas (e.g., by decreasing rotation).

In Fig. 5, the discharge quality $\beta_N H_{89P}$ is shown as a function of q_{95} for both LSN (filled) and USN (open) discharges, the predominant MHD mode is denoted by blue (m/n=3/2) and red (4/3) symbols. The curve corresponding to G=0.42 for ITER is also plotted for comparison. The best LSN performance was β_N=3.25 and H_{89P}=2.5 at q_{95}=4.3 with dRsep=-0.8 cm. The stability limit to the m/n=2/1 NTM in LSN was in the range β_N=3.3-3.5. Figure 5 shows that hybrid and AI scenarios can meet or exceed the requirements to obtain Q=10 performance in ITER, especially for q_{95}~3, for either an USN or LSN shape. From examining Figs. 4 and 5, the best performance is obtained with the m/n=4/3 NTM as this mode has less of an effect on the plasma profiles. It should also be noted that as β_N is increased above ~2.8, the m/n=4/3 NTM decreases and the m/n=3/2 becomes dominant.

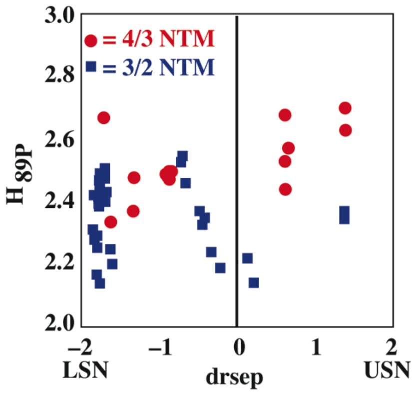

Fig. 4. Confinement as a function of the shape parameter dRsep. This dataset includes q_{95}>4.

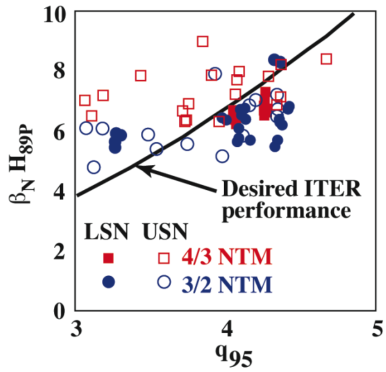

Fig. 5. Hybrid discharge performance for both LSN (filled) and USN (open) discharges with predominantly m/n=4/3 (red) and m/n=3/2 (blue).

Additional new results can be summarized here only briefly0. Hybrid discharges have been obtained in a plasma shape approximating the ASDEX shape as part of a joint experiment to compare pedestal parameters. During these experiments, hybrids were also obtained with "late heating"; preliminary analysis indicates performance is similar to the normal DIII-D scenario. "Puff and pump" heat flux reduction experiments in hybrid plasmas have shown high values of impurity entrainment η>30 for SN plasmas, but are much more sensitive to impurity injection with dRsep~0 in a balanced DN [6]. Several studies aimed at explaining the broadened hybrid current profile are in progress, including hyper-resistivity [7], conversion of the 2/2 component of the NTM to a kinetic Alfvén wave [8], and interactions between the m/n=3/2 NTM and edge localized modes. Time dependent TRANSP analysis indicates that radial redistribution of fast ions does not sufficiently affect the central current density in hybrid plasmas to maintain $q(0)$ above unity and prevent sawteeth [9].

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