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LONG-PULSE STABILITY LIMITS OF ITER BASELINE SCENARIO PLASMAS IN DIII-D

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Long-pulse Stability Limits of ITER Baseline Scenario Plasmas in DIII-D

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Long duration plasmas, stable to m/n=2/1 tearing modes (TMs), with an ITER similar shape and I_p/aB_T, have been demonstrated in DIII-D, evolving to stationary conditions with the most stable operating point at $\beta_N \approx 2$. Lower β_N, corresponding to an ITER baseline scenario 2 value of 1.8, led to a higher probability of m/n=2 tearing modes. These long pulse plasmas ($\Delta t_{duration} \leq 7.5$ s and $\leq 11\tau_R$), without electron cyclotron current drive (ECCD) for TM mitigation, have extended shorter pulse experiments in which the internal inductance, l_i, was continually evolving [1]; often TMs or locked modes occurred which would be a concern for ITER operation. The addition of ECCD allowed stable operation in plasmas with reduced torque (approximating ITER conditions) which were otherwise found to be unstable. Suppression of edge localized modes (ELMs) has also been demonstrated, utilizing a single toroidal row of internal coils (I-coils).

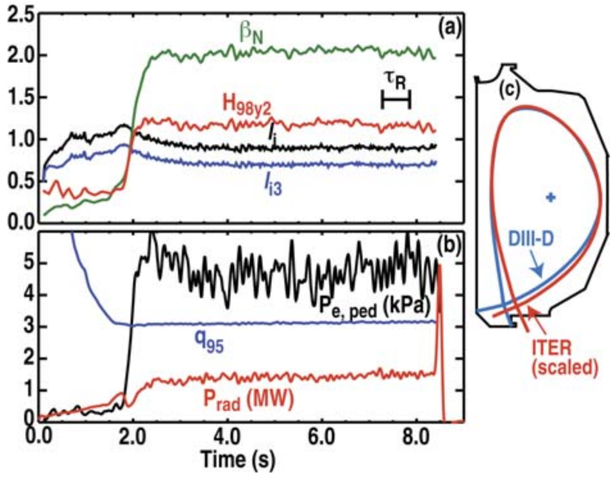

Fig. 1. Plasma with an ITER baseline shape and nearly stationary parameters, (a) β_N (green), $H_{98y,2}$ (red), l_i (black), and l_{i3}(blue); (b) electron pedestal pressure (black), total radiated power (red) and q_{95} (blue). ITER scaled shape and the DIII-D approximation is shown in (c). Plasma parameters are: I_p/aB_T = 1.40, $P_{NB} \approx 3.0$ MW.

With constant β_N maintained by neutral beam (NB) feedback control and without electron cyclotron current drive (ECCD), these plasmas have reached stationary conditions (e.g. Fig. 1). However in some cases with similar programming, m/n=2/1 tearing modes and locked modes limited the duration, indicating operation near stability limits. This was particularly evident as β_N was reduced, shown in Fig. 2. For example, 84% of plasmas were stable to 2/1 TMs with neutral beam injection (NBI) only in the co-I_p direction for $1.9 \leq \beta_N \leq 2.1$ (Fig. 2), but only 15% were stable in the ITER baseline scenario range, $1.7 \leq \beta_N \leq 1.9$. Below β_N of 1.7, where plasmas were approaching the L-H power threshold and producing long ELM-free periods, all plasmas had 2/1 TMs. The initial value of internal inductance, l_i, at the beginning of the β_N flattop phase varied from 0.9 to 1.25, but had little effect on stability to 2/1 TMs. Additional

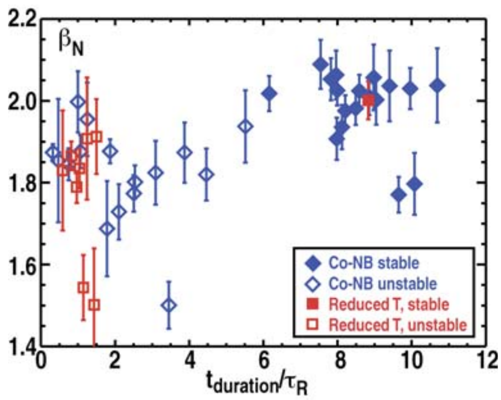

Fig. 2. Time averaged β_N as a function of duration of the flattop phase $t_{duration}$ normalized to the resistive time τ_R. Red symbols denote plasmas with a fraction of counter-I_p NBI and blue symbols denote only co-I_p NBI. All cases shown are without ECCD.

experiments are needed to further explore the dependency of l_i on stability, especially at values less than 1.0 ($l_{i3} < 0.85$).

In order to better simulate ITER conditions, neutral beam driven torque was reduced from full co-injection, ≈3 N-m at β_N≈2 (Fig. 2). However even with the addition of a small fraction of NBI in the counter-I_p direction only 10% of plasmas did not have 2/1 TMs. We note that the reduced torque phase was transient since lower confinement with counter-NBI led to additional co-NBI to maintain constant β_N.

To mitigate 2/1 TMs, especially at low torque, ECCD was applied. Broad ECCD deposition was found to be most effective when positioned near the q=3/2 flux surface plotted in Fig. 3(a). In contrast, ECCD deposition further out [black traces, Fig. 3] led to locked modes, at least for the limited database in these experiments. Although ECCD reduced the toroidal rotation [Fig. 3(c)], the plasma with ECCD near q=3/2 was sustained until the pulse was terminated [Fig. 3(d)]. In both cases, a locked mode occurred within 0.1 s after the toroidal rotation dropped to zero. We note that narrow ECCD deposition at q=2 and active tracking were not attempted in these experiments nor was sawtooth mitigation possible [2] due to technical constraints. With ECCD, long duration stationary plasmas, ≈4τ_R, at ITER relevant torques, ≈1 N-m, were achieved.

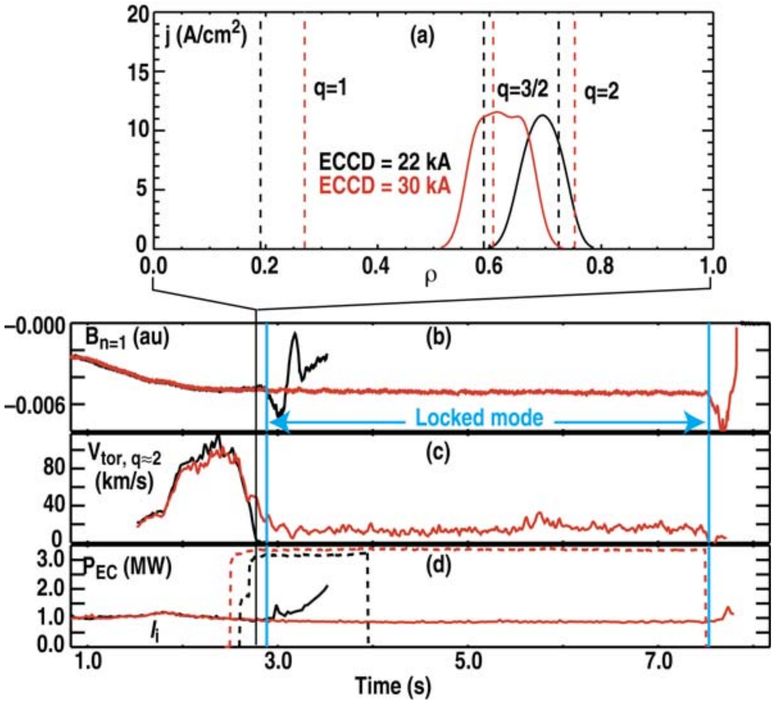

Fig. 3. (a) ECCD current density at two locations, (b) n=1 magnetic field showing the onset of locked modes, (c) toroidal velocity near the q=2 flux surface, and (d) EC power (dashed) and l_i. Both discharges had only Co-NB injection.

The DIII-D internal non-axisymmetric coils (I-coils) were also used to achieve ELM suppression in ITER baseline scenario plasmas with ECCD applied to avoid 2/1 TMs. ELM suppression at I_p/aB_T=1.38 was obtained for durations up to 1 s (the ITER design point is I_p/aB_T=1.42) with only the upper row of six I-coils, providing a broad n=3 spectrum and allowing ELM suppression at q_{95}=3.15 [3]. These plasmas, using full co-I_p NBI, were not optimized and the ELM suppression phase was limited either by m/n=1/1 MHD or the duration of ECCD.

In summary, long pulse stationary plasmas in an ITER similar shape stable to 2/1 tearing modes have successfully maintained β_N flattop values up ≈11 τ_R under a variety of conditions, with most reliable operation at β_N≈2. This extended previous work [1] with shorter pulses in which plasmas evolved until the onset of TMs. The fraction of long pulse plasmas at the ITER baseline scenario β_N value of ≈1.8, was much lower, indicating operation closer to stability limits.

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