Edge Stability and Performance of the ELM-Free Quiescent H-Mode and the Quiescent Double Barrier Mode on DIII–D*

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The quiescent H (QH) mode is an ELM-free, high-confinement mode that combines well with an internal transport barrier to form quiescent double barrier (QDB) stationary state, high performance plasmas [1]. The QDB mode achieves performance of $\beta_N H_{89} \sim 7$ in quasi-stationary conditions for a duration of 10 τ_E, limited by hardware. Recently we have demonstrated stationary state QDB discharges with little or no change in the plasma density, temperature, radiation power, and q profiles with $q_0 \sim 1.2$ for ~2 s, again limited by hardware [2]. This performance is roughly equal to that of the ELMing "hybrid scenarios" currently under investigation as ITER operating modes, yet without the impulsive wall heating effects of ELMs. The achievement of a high-performance ELM-free mode has important implications for reactor grade devices such as ITER, and other tokamaks have begun investigations of QH mode, including ASDEX Upgrade, and JT-60U, and JET. In this paper we will report on: 1) the advances in performance of the QDB discharges, including demonstrations of plasma profile control, 2) the progress made on QH mode edge profile analysis, leading to an indication that ELM suppression results from a reduction of the edge bootstrap current compared to ELMing phases and 3) a demonstration that QH mode can simultaneously achieve pedestal values of β_N and ν^* equal to those expected in ITER.

The QH pedestal profiles of n_e, n_{C+6}, T_e, T_i, v_{tor}, and v_{pol} are measured using Thomson scattering, reflectometry, and charge exchange recombination spectroscopy. From these measurements other important edge profiles are derived, including: the total kinetic pressure, the radial electric field, and the neoclassical bootstrap current [3]. Figure 1 shows a comparison of ELMing and QH phases of (a) the edge pressure gradient, and (b) the bootstrap current profiles calculated using the measured profiles in the NCLASS model. Bootstrap current has a stronger dependence on density gradient than temperature gradient, and the edge bootstrap is smaller during the QH phase primarily due to a lower edge density

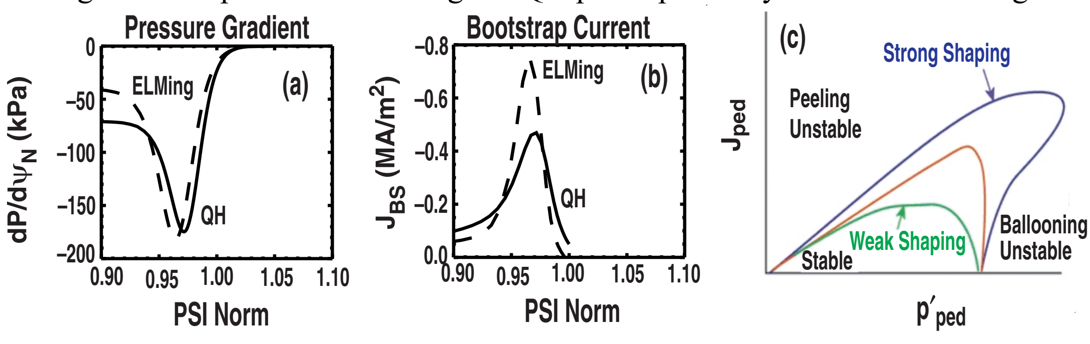

Fig. 1. The edge pressure gradient profiles during the ELMing and QH phases of counter injected discharge 106919 are shown in (a). The edge bootstrap current profile from NCLASS using the measured profiles is shown in (b). A stability diagram for edge localized peeling/ballooning modes derived from the ELITE model is shown in (c).

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gradient. The coupled peeling/ballooning mode stability limit from the ELITE model is shown schematically in (c). The data and theoretical guidance in Fig. 1 suggest that the QH mode lies along the peeling mode stability boundary and that the ELMs are a current driven instability. This interpretation is supported by current ramp experiments. Upward ramps quickly, <20 ms, initiate ELMing activity, while QH is stable during a downward ramp. Following guidance from ELITE, Fig. 2(c), increasing the triangularity during QH mode led to higher density QH discharges with pedestal β_N and ν^* equal to those expected in ITER.

A distinctive feature of QH-mode is an unusually deep and narrow radial electric field well observed at the edge [4]. In addition, QH has only been observed in counter injection, which is prone to prompt beam ion loss. The relationship of E_r to prompt beam ion loss was evaluated by changing between the two beam injection angles available on DIII-D, as shown in Fig. 2(a). Ion orbit calculations, Fig 2(b), indicate that edge ionization of "left beams" results in prompt loss, but not for the "right beams". While edge rotation does change as expected, E_r does not change significantly, suggesting that prompt beam ion loss is not causal. However, QH mode was observed to be more robust with left beam injection, indicating that fast ion loss plays a role. Although right beam ions are not lost promptly, these fast ions can readily be directed into loss orbits via small angle scattering. The electric field well during the QH phase is accompanied by very strong E×B shear. The effect of E_r and E×B shear on edge stability is not understood at this time. Detailed stability analysis using ELITE with current profiles and equilibria consistent with the edge bootstrap current is in progress. During 2004 analysis using a new version of ELITE with toroidal rotation will begin.

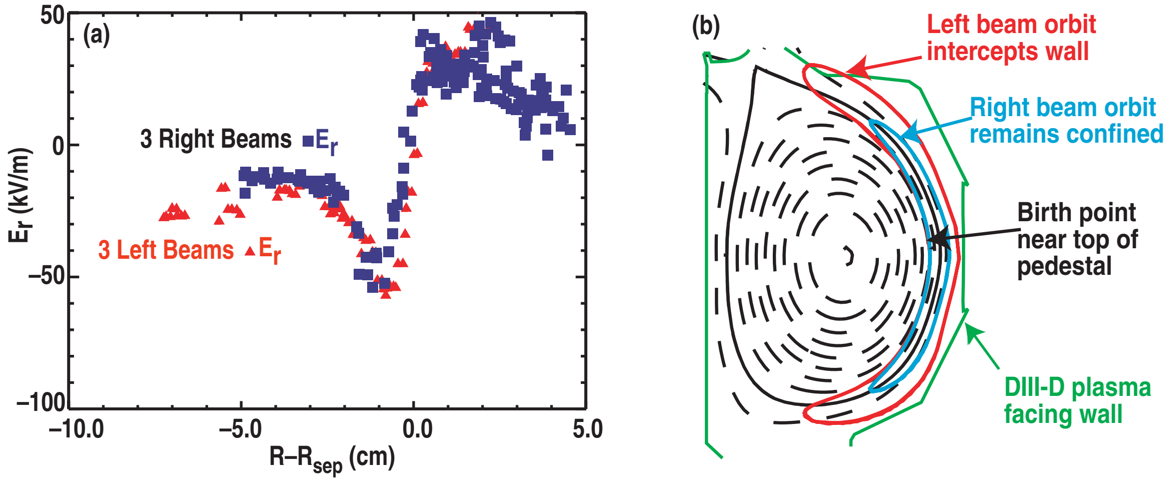

Fig. 2. (a) The edge radial electric field for a QH with (left beams) and without (right beams) prompt fast ion loss. The ELMing phase has a well depth of –20 kV/m. (b) Calculated orbits of beam ions originating near the pedestal during QH mode. Left beams have a tangency radius of 1.2 m, while right beams are tangent at 0.75 m.

In addition to the advances made in performance of QDB discussed above, we have demonstrated profile control capabilities. The density and impurity peaking previously reported in QDB can be mitigated using central ECH. Also, the pedestal density can be increased by >2x by scanning the shape to higher triangularity and magnetic balance. During 2004 we plan to demonstrate increased β during QDB at high triangularity.

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