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ADVANCING THE PHYSICS BASIS OF QUIESCENT H-MODE THROUGH EXPLORATION OF ITER RELEVANT HIGH DENSITY OPERATION

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Advancing the Physics Basis of Quiescent H-mode Through Exploration of ITER Relevant High Density Operation

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Recent experiments on DIII-D have overcome a long-standing limitation in accessing quiescent H-mode (QH-mode) at high Greenwald density fraction (Fig. 1), a high confinement state of the plasma that does not exhibit the explosive instabilities associated with edge localized modes (ELMs). Comparisons of the dependence of the maximum density threshold for QH-mode with plasma shape validate the underlying theoretical peeling-ballooning models describing ELM stability. High density QH-mode operation with strong shaping has allowed stable access to a previously predicted regime of very high pedestal dubbed "Super H-mode" [1] (Fig. 2). Importantly, QH-mode achieves ELM-stable operation while maintaining adequate impurity exhaust, due to the enhanced impurity transport from an edge harmonic oscillation (EHO), thought to be a saturated kink-peeling mode driven by rotation shear. Together with the simultaneous achievement of high beta, high confinement and low q_{95} for many energy confinement times, these results suggest QH-mode as a potentially attractive operating scenario for ITER's Q=10 mission.

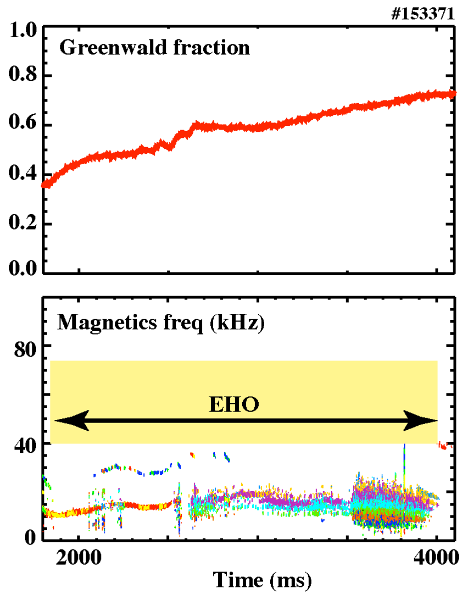

Fig. 1. QH-mode maintained to high Greenwald fraction in strongly shaped plasma.

Through the use of strong shaping, QH-mode plasmas have been maintained at high densities as shown in Fig. 1, both absolute ($\bar{n}_e >\ 7\times10^{19}$ m^{-3}) and normalized to the Greenwald density ($\bar{n}_e/n_G > 0.7$, where $n_G = I_p/\pi a^2$ is the Greenwald density for plasma current I_p in MA and minor radius a in m). In these plasmas, gas puffing is added during the QH-mode phase, controlled via density feedback to follow a ramping density target. The plasma remains ELM stable until a threshold in density is reached. The EHO mode number

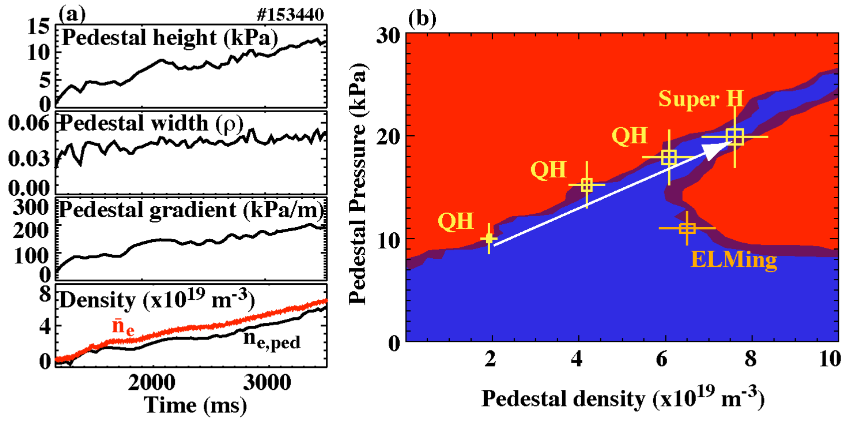

Fig. 2. QH-mode pedestal pressure height, width, and gradient all increase as the density is increased, as predicted for plasmas operating along the kink-peeling boundary. EPED modeling shows that the trajectory of increasing density provides access to a second ELM-stable regime (Super H-mode) at high pedestal parameters.

typically remains relatively constant during the density variation, until just prior to the return of ELMs, when the EHO appears to become less coherent.

The pedestal is found to evolve to levels comparable with some of the highest performance transient pedestals seen on DIII-D, consistent with EPED [2] analysis of the pedestal height and width. At fixed β_N, the height, width and gradient of the pedestal pressure all increase as the density increases, as shown in Fig. 2, and the increase in the density originates from the pedestal rather than via a peaking of the density profile. The excellent agreement between the experimental measurements and theory provides strong evidence that the EPED model can accurately describe the pedestals of plasmas in the kink-peeling regime, which is an important criterion for access to QH-mode, together with rotation shear [3,4]. Similar stability calculations using ITER's shape and other expected parameters predict that the ITER pedestal will naturally operate on the kink-peeling boundary where QH-mode can exist, even for pedestal densities exceeding $10^{20}\,m^{-3}$, a value significantly higher than the ITER design value. Accordingly, ITER's pedestal will be in the QH-mode parameter range of density and collisionality.

The present high density QH-mode plasmas are found to access a second ELM stable region as shown in Fig 2. The challenge for accessing this regime is that a plasma running with fixed high density will necessarily encounter the lower pedestal solution first, inhibiting access to the high pedestal pressure solution predicted by EPED. In these experiments, by raising the density dynamically once the low collisionality QH-mode edge has formed along the kink-peeling boundary, these QH-mode plasmas avoid encountering the lower pedestal solution and enter a “channel” of high pressure and density that is otherwise inaccessible. This shows that the QH-mode parameter space is not characterized by physics associated with low density, but rather is correctly described by peeling-ballooning theory.

Measurements of the impurity confinement time of non-recycling impurity fluorine have demonstrated that the EHO provides superior impurity exhaust relative to ELMs. This is an important result, because there is concern that ELM-stable regimes may suffer unacceptable impurity accumulation, and while ELMs are undesirable with respect to the potentially damaging periodic divertor heat loads, they are beneficial in terms of preventing impurities from accumulating in the core plasma. In addition, although the measured ExB shear is found to increase at low toroidal rotation, resulting in reduced turbulence and increased energy confinement, the impurity confinement time is not affected by rotation.

Experiments have extended QH-mode to high normalized fusion performance, $G = \beta_N H_{89}/q_{95}^2$, with values for the confinement factor H_{89}, β_N and q_{95} sustained at ITER relevant values for many energy confinement times in an ITER similar shape, as shown in Fig. 3. Taken as a whole, the compatibility of QH-mode with high performance, high density, low torque operation, in a regime that is ELM stable while maintaining excellent impurity exhaust, suggests QH-mode as a potentially attractive operating scenario for succeeding in ITER's Q=10 mission.

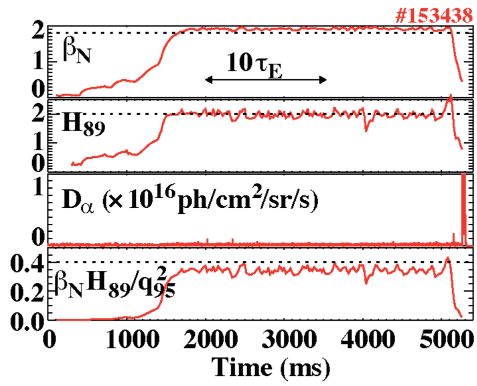

Fig. 3. Demonstration of QH-mode sustained at ITER relevant parameters (dashed lines) for nearly $20\tau_E$.

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