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Abstract. Recent experiments on DIII-D have overcome a long-standing limitation in accessing quiescent H-mode (QH-mode), a high confinement state of the plasma that does not exhibit the explosive instabilities associated with edge localized modes (ELMs). In the past, QH-mode was associated with low density operation, but has now been extended to high normalized densities compatible with operation envisioned for ITER. Through the use of strong shaping, QH-mode plasmas have been maintained at high densities, both absolute ($\bar{n}_e \approx 7 \times 10^{19}$ m^{-3}) and normalized Greenwald fraction ($\bar{n}_e/n_G > 0.7$) . In these plasmas, the pedestal can evolve to very high pressures and current as the density is increased. Calculations of the pedestal height and width from the EPED model are quantitatively consistent with the experimental observed evolution with density. The comparison of the dependence of the maximum density threshold for QH-mode with plasma shape help 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". In general, QH-mode is found to achieve ELM-stable operation while maintaining adequate impurity exhaust, due to the enhanced impurity transport from an edge harmonic oscillation, thought to be a saturated kink-peeling mode driven by rotation shear. In addition, the impurity confinement time is not affected by rotation, even though the energy confinement time and measured $E \times B$ shear is observed to increase at low toroidal rotation. Together with demonstrations 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.

1. Introduction

Future burning plasma devices such as ITER [1] are typically designed assuming H-mode levels of confinement, but require a plasma edge regime that keeps divertor heat loads to an acceptable level. However, standard H-mode is associated with steep gradients in the plasma edge forming the so-called pedestal, and these strong gradients are observed to trigger edge localized modes (ELMs) [2], resulting from exceeding the peeling-ballooning stability limit.

Although ELMs prevent impurity accumulation in the core, they may lead to unacceptable divertor heat loads in a device such as ITER [3]. As such, significant effort is being spent to investigate external means of either eliminating or at least reducing the heat fluxes from ELMs, all while retaining the positive benefits of impurity flushing and without compromising the pedestal height.

An ideal solution to eliminating ELMs is to utilize scenarios that are peeling-ballooning stable, but which still possess good H-mode confinement, such as Quiescent H-mode (QH-mode) [4] or I-mode [5]. In QH-mode, the transport associated with ELMs is replaced by a benign "edge harmonic oscillation" (EHO) [4], which limits the plasma to just below the peeling-ballooning stability limit. The following sections cover recent advances in qualifying QH-mode as a possible operating scenario to meet ITER's $Q = 10$ mission.

2. High Normalized Fusion Performance in QH-mode

Recent experiments have extended QH-mode to high normalized fusion performance, $G = \beta_N H_{89}/q_{95}^2 \approx 0.36$ approaching the level required for $Q = 10$ performance on ITER ($G \approx 0.42$), 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. 1.

To date, these results have been achieved in plasmas with significant counter NBI torque. As reported previously, the confinement in QH-mode is actually found to increase as the torque and rotation is reduced toward balanced torque injection [6], so one anticipates that these results will be significantly improved at low torque. However, efforts to investigate this so far have been hampered by locked modes observed at lower q_{95} and low torque. In particular, while QH-mode is robustly maintained at $\beta_N \approx 2$ through zero torque at $q_{95} \gtrsim 4.5$ with the use of $n = 3$ non-axisymmetric fields to maintain the edge rotation for QH-mode, increasing levels of (counter) NBI torque have been required to avoid locked modes as q_{95} is reduced, and at $q_{95} \approx 3.3$ it has proven difficult to reduce the torque below about 2 Nm.

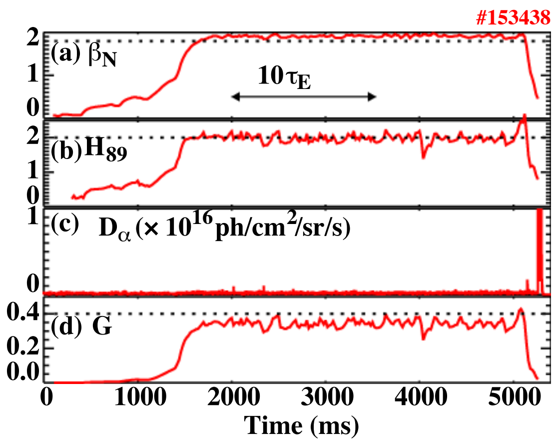

FIG. 1. High performance QH-mode: (a) β_N; (b) H_{89} factor; (c) D_α brightness and; (d) normalized fusion performance $G = \beta_N H_{89}/q_{95}^2$.

Recent analysis has indicated that this may be the result of a large $n = 1$ error field that is introduced together with the desired $n = 3$ field from the coils. While the vacuum $n = 1$ field is very small, there is large amplification of this field in the plasma. Future experiments will investigate whether the limitation in low torque, low q_{95} QH-mode can be overcome with improved error field compensation.

3. Impurity Transport Driven by the EHO

Adequate transport of impurities is essential for maintaining a high fuel-ion ratio and high performance. In standard ELMing H-mode, impurity accumulation is avoided by the periodic particle expulsion from each ELM. However, since ELM mitigated or suppressed regimes are required for ITER to prevent excessive damage to plasma facing components, it is critical that any solution for the large heat fluxes associated with the ELMs be able to maintain adequate impurity transport.

Measurement of particle transport is complicated due to uncertainties in the particle source terms, particularly due to recycling from the wall. Therefore, impurity transport measurements are best made using a species that is not typical in the tokamak and does not return to the plasma core. For these studies, carbon tetrafluoride (CF_4) was injected into the plasma, with charge exchange recombination (CER) spectroscopy measuring the F-IX (10-9) transition at 4796 Å. The impurity confinement time τ_P is readily determined from the exponential decay of the signal [7].

Figure 2 shows the uptake and exhaust of F impurity following a 5 ms gas puff of CF_4. It is clear from these time histories that the decay rate of F is faster at lower density. A wider database of discharges shows the dependence of the F impurity confinement time on the density for both QH-mode discharge and ELMing discharges. One can identify a clear correlation between the impurity confinement time and density in the QH-mode phase. Importantly, one sees that at comparable densities, the QH-mode plasmas have impurity confinement times at least as short as regular ELMing plasmas [7], although it should be noted that in these conditions the ELMs were relatively infrequent.

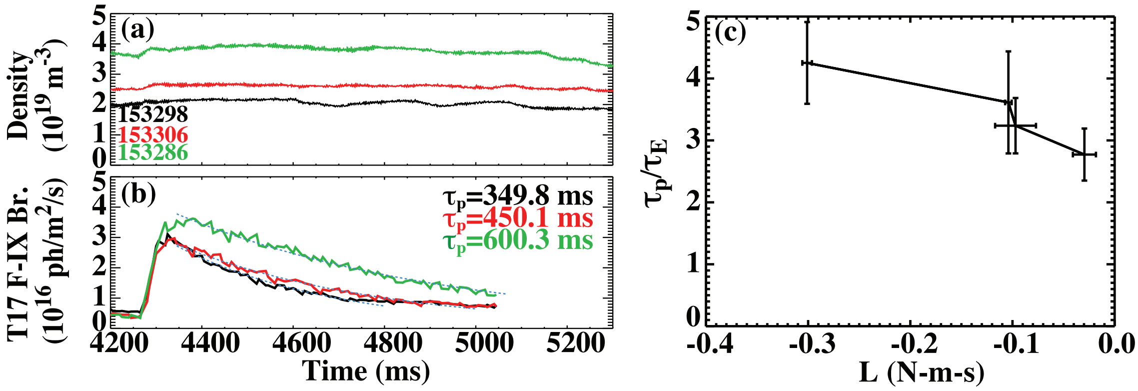

FIG. 2. (a) Line average density and (b) F emission. (c) Ratio of τ_P/τ_E as a function of the angular momentum in QH-mode plasmas, scanned here through controlled variation of the neutral beam torque.

As previously noted, QH-mode plasmas exhibit increased energy confinement as the torque and rotation are reduced. Importantly, τ_P is found to be insensitive to the rotation, such that the ratio τ_P/τ_E actually decreases in the more reactor relevant range of low rotation (Fig. 2). Similar studies have also shown that τ_P is insensitive to the level of applied non-axisymmetric field [7].

4. Extension of QH-mode to ITER Relevant Densities

QH-mode has historically been associated with low density operation, and indeed, the general recipe for achieving robust QH-mode has been to work on limiting the fueling and reducing the density. While QH-mode operation is therefore associated with low collisionality as envisioned in a future reactor, the low normalized density associated with QH-mode has been an outstanding criticism about the applicability of the scenario to a device like ITER.

To address this long-standing issue, experiments were conducted to investigate the upper limits in density for QH-mode operation [8]. In particular, gas puffing was added during the QH-mode phase, controlled via density feedback to follow a pre-programmed ramping density target. In this way, the maximum tolerable density compatible with QH-mode was determined as indicated by the return of ELMs. An example of this is shown in Fig. 3, contrasted with typical QH-mode operation, where little if any gas is puffed, a prescription that produces the a strong EHO and the cleanest QH-mode performance.

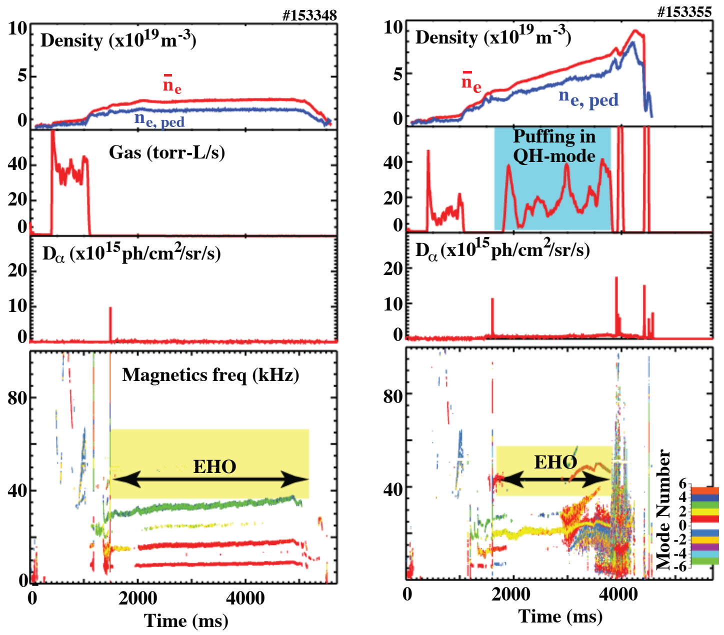

FIG. 3. Density, gas, D_α light and magnetic spectrogram for typical QH-mode (left), and QH-mode with density ramp and strong gas puffing (right).

Peeling-ballooning theory predicts that shaping should provide one of the strongest knobs for affecting the maximum tolerable density in QH-mode [9]. The EHO is believed to be the saturated state of a current-driven mode encountered along the kink-peeling boundary, for which rotation shear is destabilizing [9]. As such, operation along the kink-peeling boundary is thought to be an essential requirement for access to QH-mode, and experimentally, plasmas with an EHO are always found to exist along this boundary. At low triangularity, operation along the kink-peeling boundary is only possible at very low densities, with higher density and collisionality driving the plasma toward the ballooning boundary. With stronger shaping, the stability boundary is calculated to widen, allowing QH-mode operation at higher densities.

Experiments have confirmed this trend in a scan of the minimum in the upper and lower triangularity of the plasma shape, $\delta \equiv \min(\delta_{\text{upper}}, \delta_{\text{lower}})$, with other key parameters such as toroidal field and plasma current and heating power held constant (Fig. 4). This data shows that plasmas with high triangularity can sustain QH-mode at twice the density of plasmas with reduced triangularity. With high triangularity, QH-mode plasmas have been maintained at high normalized densities as shown in Fig. 5, (Greenwald fraction $\bar{n}_e/n_G > 0.7$, where $n_G = I_p/\pi a^2$ is the Greenwald density limit for tokamaks [10]). This demonstrates that low density is not an inherent requirement for QH-mode operation.

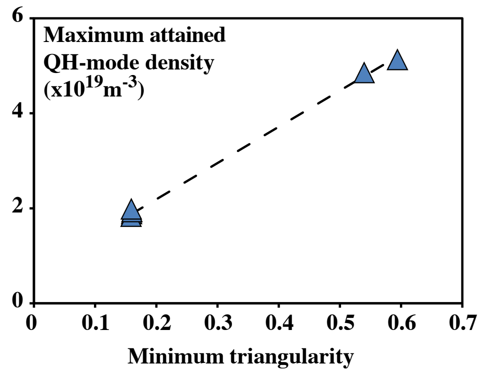

FIG. 4. Maximum attainable QH-mode density as a function of triangularity at fixed plasma current and toroidal field.

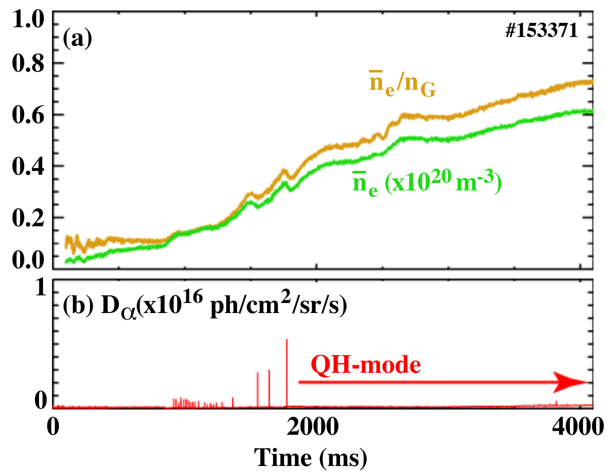

FIG. 5. (A) Line average and Greenwald fraction; and (b) D_α light, showing high Greenwald fraction QH-mode operation.

With strong shaping, the QH-mode pedestal height is found to evolve to levels comparable with some of the highest performance transient pedestals seen on DIII-D. At fixed β_N, maintained with β_N feedback control of the neutral beam power, the height, width and gradient of the pedestal pressure all increase as the density increases, and the increase in the density originates from the pedestal rather than via a central peaking of the density profile.

Calculations of the expected pedestal evolution from EPED [11] are quantitatively consistent with the experimental measurements [8], as shown in Fig. 6. Similar EPED calculations using the ITER shape and other expected parameters find that the ITER pedestal will operate on the kink-peeling boundary where QH-mode can exist for all pedestal densities up to values exceeding 10^{20} m^{-3}, which is significantly higher than the baseline ITER $Q = 10$ scenario requirement [12].

5. Access to Super H-mode

Application of the EPED model has revealed that a second region of ELM-stable operation is possible in strongly shaped plasmas at high density, characterized by very high pedestals. This new regimes has been dubbed "Super H-mode" [13]. Realizing this high pedestal state is a challenge because at fixed density, the plasma will encounter the lower pedestal solution first, preventing access to the high pedestal pressures predicted by EPED.

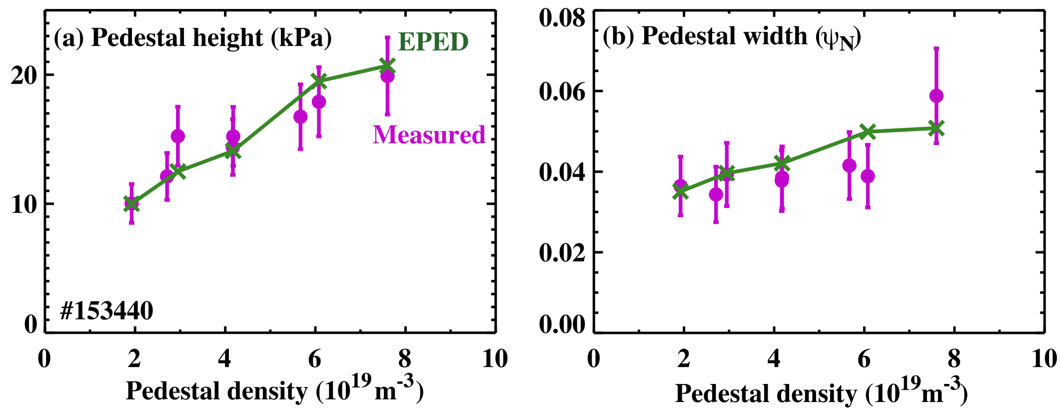

FIG. 6. (a) Pedestal height and (b) pedestal width as a function of the pedestal density for both experiment (magenta) and calculations from EPED (green).

The time-evoling density trajectories in the high density QH-mode plasmas appear to have overcome this problem and accessed the Super H-mode regime [8] as shown in Fig. 7. For pedestal densities above approximately 6×10^{19} m^{-3}, EPED finds two separate regions for ELM stable operation. By first establishing QH-mode at low collisionality, it has been possible to traverse the kink-peeling boundary and enter the "channel" of high pedestal pressure, avoiding the lower pedestal solution. In this discharge, an ELM eventually is triggered, which drops the plasma out of the Super H-mode channel and down to the lower pedestal solution, resulting in nearly a factor of two reduction in the pedestal pressure with only a modest decrease in density. Therefore, the experimental trajectory in Fig. 7 demonstrates a bifurcation in the pedestal height at high density, as predicted by EPED.

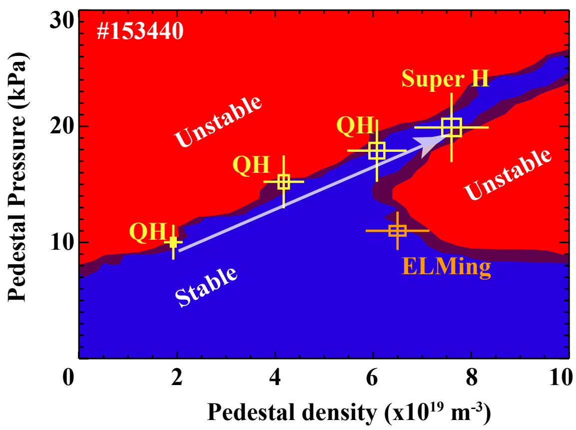

FIG. 7. Experimental trajectory of QH-mode pedestal into predicted Super H-mode regime of high pedestal and bifurcation to lower pedestal ELMing state.

The thermal energy confinement time is found to increase as the density and pedestal evolve to higher values, as seen in Fig. 8(a). Here, the thermal energy confinement time is computed from the measured density and temperature profiles and the neutral beam power and fast ion energy content calculated with TRANSP [14]. The confinement time rises more than 50% before a $m/n = 3/2$ tearing mode is destabilized and impacts the core confinement. The increasing thermal energy confinement would be expected in a plasma with an increasing pedestal height but stiff core transport. Indeed, the total thermal stored energy increases, owing to contributions from both the pedestal and core [Fig. 8(b)]. Therefore, the strong gas puffing used to fuel the plasma and raise the pedestal pressure does not lead to a degradation of core confinement. More detailed transport analysis confirms that the core thermal transport is actually modestly reduced, as seen by the decrease in both the ion and electron thermal diffusivities shown in Figs. 8(d, e). This reduced transport is consistent with low wavenumber ($k_\perp < 3$ cm^{-1}, or $k_\perp \rho_i < 1$) density fluctuation measurements from the beam emission spectroscopy diagnostic, which observes that the time-resolved fluctuation amplitude decreases as the pedestal increases.

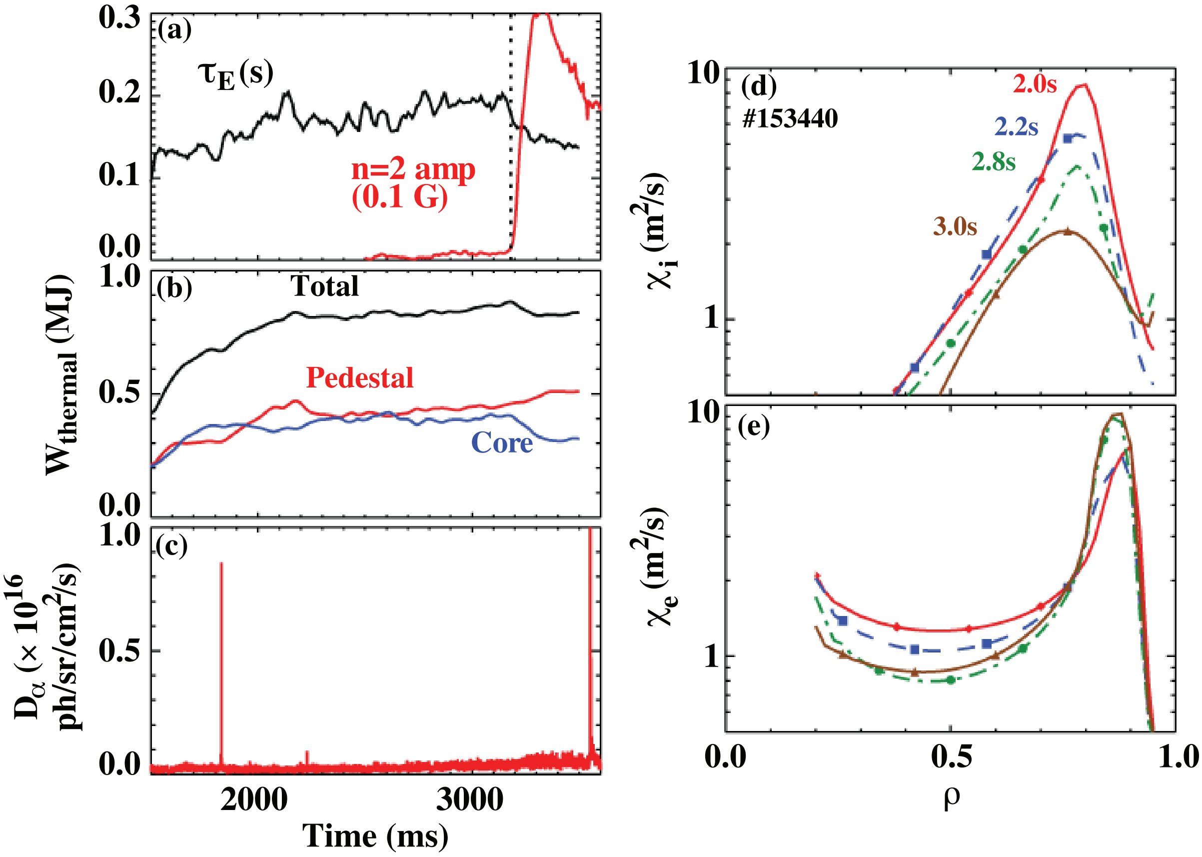

FIG. 8. (a) Thermal energy confinement time and $n = 2$ amplitude; (b) thermal energy content; (c) D_α light; (d) ion and (e) electron thermal diffusivity profiles as a function of time.

The return of ELMs appears to be related to the loss of rotation shear [15], rather than an inherent transition from the current-driven kink-boundary to the pressure-driven ballooning-boundary. Reduced rotation and rotation shear arises due to the reduction in the injected torque per particle as the density increases, together with an increase in the co-current directed intrinsic torque [16, 17] as the pedestal gradients increase, which opposes the counter rotation driven by the counter-current beams used in these experiments. More detailed analysis has found that the shear in $\omega_E = E_r/RB_\theta$, the rotation driven by the radial electric field E_r may be the relevant quantity for QH-mode, and the shear in ω_E is found to be below the empirical boundary described in Ref. [6] when the ELMs return.

Experimental evidence of a second region of edge stability characterized by enhanced pedestal pressure suggests a path for significantly improving the performance of a fusion power plant. Assuming stiff core transport, the achievable fusion gain is strongly dependent on the pedestal height, so there is high leverage in exploiting a regime with pedestals much higher than typical H-mode conditions and the EPED predictions presented in

Fig. 7 indicate that much higher pedestals may yet still be possible. Nonetheless, at this time, the appearance of core tearing modes in the Super H-mode plasmas is such that the full potential of the regime in terms of confinement and performance has not yet been realized.

6. Conclusions

Recent experimental work in QH-mode suggests that it may be the most attractive operating scenario for succeeding in ITER's Q=10 mission. It exhibits inherently ELM-stable operation at ITER relevant values of β_N, H_{89}, q_{95}, torque and density, while maintaining adequate impurity exhaust. In addition, it has provided access to a new regime of very high pedestals called "Super H-mode", which if successfully exploited may open the path to much higher performance than currently achievable in standard H-mode.

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