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Abstract

A path to a new high performance regime has been discovered in tokamaks that could improve the attractiveness of a fusion reactor. Experiments on DIII-D using a quiescent H-mode edge have navigated a valley of improved edge peeling-ballooning stability that opens up with strong plasma shaping at high density, leading to a doubling of the edge pressure over standard edge localized mode (ELM)ing H-mode at these parameters. The thermal energy confinement time increases both as a result of the increased pedestal height and improvements in the core transport and reduced low-k turbulence. Calculations of the pedestal height and width as a function of density using constraints imposed by peeling-ballooning and kinetic-ballooning theory are in quantitative agreement with the measurements.

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Future burning plasma devices require a plasma edge regime that keeps divertor heat loads to an acceptable level, while maintaining sufficient core performance. Devices such as ITER [1] are typically designed assuming H-mode levels of confinement. 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], believed to be a consequence of crossing the peeling-ballooning stability limit. More specifically, strong pressure gradients drive high toroidal mode number $n > 20$ ballooning instabilities, while the edge current density (primarily from the bootstrap current) tends to be stabilizing for high n ballooning modes, but provides the drive for low to intermediate n kink-peeling instabilities. Since the bootstrap current increases with reduced collisionality, the plasma tends to encounter the low n kink-peeling boundary at low collisionality, and moves toward higher n numbers and the ballooning boundary as the collisionality is increased.

While ELMs are found to be beneficial in terms of preventing impurity accumulation in the core, they can lead to unacceptable heat loads in a device such as ITER [3]. As such, significant effort is being spent to investigate external means of either eliminating [4–7] or reducing the size [8–13] of ELMs, while retaining the positive benefits associated with impurity flushing and without compromising the pedestal height. The latter is especially important, because core transport in burning plasma regimes is typically predicted to be very stiff (that is, turbulent transport processes act to inhibit profiles from steepening beyond a certain critical gradient), such that the edge pedestal height can strongly influence the fusion gain [14]. Therefore, there is a strong incentive to investigate ELM-stable solutions at the maximum achievable pedestal pressure.

An ideal solution to eliminating ELMs is to exploit operating regimes that are naturally peeling-ballooning stable, but which still possess good H-mode confinement, such as Quiescent H-mode (QH-mode) [15] or I-mode [16]. In QH-mode, the transport associated with ELMs is replaced by a benign "edge harmonic oscillation" (EHO) [15], which limits the plasma to just below the peeling-ballooning stability limit. In the past, this mode of operation required rapid levels of rotation, but recent efforts have extended QH-mode plasmas to more reactor relevant regimes with low levels of rotation [17]. Furthermore, the EHO associated with QH-mode has been found to be at least as efficient at expelling impurities as ELMs [18]. Hence, QH-mode appears to be a promising scenario for a burning plasma device.

Still, a major perceived shortcoming of the QH-mode regime has been its association with low density operation. As such, its applicability to a fusion reactor anticipated to run at high normalized density for optimum fusion power production has been called into question. The experiments described in this Letter were guided by predictions from peeling-ballooning theory, which suggested that shaping should be an important parameter affecting the maximum tolerable density in QH-mode [19], and in fact that with sufficient shaping, access to a region of parameter space characterized by very high pedestal density, pressure and current, dubbed "Super H-mode", becomes possible [20]. Therefore, the density threshold in QH-mode was explored on DIII-D as a function of shaping, in particular where the minimum of the upper and lower triangularity, $\delta_{\rm min} = \min(\delta_{\rm upper}, \delta_{\rm lower})$, was varied from $0.15 \lesssim \delta_{\rm min} \lesssim 0.6$. At the higher values of $\delta_{\rm min}$, QH-mode plasmas could be maintained at high densities, both absolute ($\bar{n}_e \approx 7 \times 10^{19}$ m^{-3}) and normalized Greenwald fraction ($\bar{n}_e/n_G > 0.7$, where $n_G = I_p/\pi a^2$ is the Greenwald density limit for tokamaks [21]). This clearly illustrates that low density is not an inherent requirement for QH-mode operation or EHO sustainment. An example is shown in Fig. 1, where strong gas puffing has been 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, after which ELMs return. The reproducibility of finding the QH-mode density threshold with this technique in repeat shots proved to be very high, typically better than 5%. The EHO is found to change character in terms of dominant mode number as the density increases, and becomes less coherent and more broadband in nature as the density approaches the threshold.

Figure 2 shows the dependence of the maximum attainable QH-mode density as a function of $\delta_{\rm min}$, with other key parameters such as toroidal field ($B_T \approx 1.9$ T), plasma current ($I_p \approx 1$ MA) and β_N (≈ 1.9) held constant. In this data, plasmas with strong shaping and high triangularity sustain QH-mode at more than twice the density of plasmas with reduced triangularity at the same plasma current. Since the Greenwald density limit does not have an explicit dependence on triangularity (and the difference in minor radius varies by less than 2% with these shape changes), it is apparent that the maximum tolerable density for sustainment of the EHO cannot be characterized in terms of a maximum in the Greenwald density fraction. A similar increase in the maximum QH-mode density with triangularity is seen across the broader dataset spanning $0.7 < I_p < 1.5$ MA, corresponding to edge safety factors $3.3 < q_{95} < 7.3$.

The change in the density threshold with shaping can be understood by consideration of the EHO. The EHO is thought to be the saturated state of a current-driven mode for which rotation shear is destabilizing [19]. The perturbation associated with the current-driven mode causes an electromagnetic torque exchange with the wall, thereby reducing the rotation and providing a saturation mechanism that prevents the mode from evolving into an ELM. On the other hand, rotation shear is predicted to be stabilizing for higher n ballooning modes, and therefore saturation via this mechanism is not possible. Hence, operation along the kink-peeling boundary is considered an essential requirement for QH-mode operation, and indeed, experimentally, plasmas with an EHO are always found to exist along this boundary. For weak shaping, the current-driven kink-peeling boundary is only accessible at low density and collisionality where the edge current density driven by the bootstrap mechanism is high, while higher densities with reduced bootstrap current instead encounter the pressure driven peeling-ballooning limit. As the shaping is increased, the stability boundary is calculated to expand into regions of higher current and pressure, widening the density range over which the plasma encounters the kink-peeling boundary [19]. Therefore, the data in Fig. 2 is compatible with this theoretical expectation.

It is observed that in these plasmas with strong shaping, the pedestal evolves to very high pressures and current densities as the plasma density is increased. In fact, the pedestal plasma parameters become comparable to some of the highest performance pedestals ever achieved even transiently on DIII-D. More specifically, at fixed triangularity and β_N, maintained with β_N feedback control, the height, width and gradient of the pedestal pressure all increase with density, as shown in Fig. 3. Predictions of the pedestal height and width are made using the EPED model [22] which takes scalar inputs of various quantities including the toroidal field, β_N and various shaping parameters. From these, the pedestal height is solved as a function of width for both kinetic ballooning modes (KBMs) and similarly for peeling-ballooning modes, with the intersection of these two curves giving the EPED solution. For these QH-mode plasmas, EPED predicts increasing pedestal pressure as a function of time and increasing density, which is characteristic of traversing along the low collisionality kink-peeling boundary. Moreover, the calculation of the expected pedestal evolution from EPED are quantitatively consistent with the experimental measurements. In particular, one sees that the increase in the pedestal height by a factor of 2 throughout the density ramp is accurately reproduced in Fig. 3, and the overall magnitude and trend of the pedestal width is also found to be consistent.

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 high density kink-peeling regime. Similar calculations using ITER's shape and other expected parameters predict that the ITER pedestal will naturally operate on the kink-peeling boundary, even for pedestal densities exceeding 10^{20} m^{-3} [23], a value significantly higher than that required for the ITER $Q = 10$ reference operational scenario. Accordingly, the present benchmarking of EPED against high density QH-mode provides increased confidence that ITER's pedestal will be in the QH-mode parameter range of density and collisionality.

A significant change in the fast ion content occurs in these plasmas as the density increases. When the plasma is first initiated at low density, the fast ion energy content relative to the total stored energy is comparatively high, $W_{\text{fast}}/W \approx 0.3$, which is fairly typical for QH-mode on DIII-D. However, as the density increases and the electron temperature decreases (at fixed β_N), the slowing down time of the fast ions drops significantly, resulting in an effective conversion of fast ion energy to thermal energy, with the absolute fast ion energy content reduced by two thirds, and the fast ion fraction falling below 10%.

Previously it has been found that rotation shear is an essential requirement for enabling QH-mode conditions [24]. The first occurrence of an ELM in these high triangularity, high density QH-modes appears to be related to the loss of rotation shear, rather than an inherent transition from the current-driven kink-boundary to the pressure-driven ballooning-boundary. Indeed, EPED calculations suggest that the pedestal density and pressure can in principle be raised significantly further. Reduced rotation and rotation shear arises because of a reduction in the injected torque per particle as the density increases, together with an increase in the co-current directed intrinsic torque [25, 26] as the pedestal gradients increase, which opposes the counter rotation driven by the counter-current beams used in these experiments. More detailed study has suggested that the shear in $\omega_E = E_r/RB_\theta$, the rotation driven by the radial electric field E_r, provides a better distinction between QH-mode and ELMing conditions [17]. While the increasing diamagnetic contribution to E_r associated with the increasing pedestal pressure partially compensates for the reduced toroidal rotation, the shear in ω_E nonetheless decreases and is below the empirical boundary described in Ref. [17] when the ELMs return.

The thermal energy confinement time increases as the density and pedestal evolve to higher values, a result that might be expected from a rising pedestal coupled with stiff core transport. This can be seen in Fig. 4(a), which shows the thermal energy confinement time computed from the fitted density and temperature profiles, with the neutral beam power and fast ion energy content calculated with TRANSP [27]. The confinement time rises more than 50% before a $m/n = 3/2$ tearing mode is destabilized and begins to impact the core confinement, even though the pedestal pressure continues to rise for some time before the return of ELMs. The total thermal stored energy is observed to increase, arising from increases in contributions from both the pedestal and core [Fig. 4(b)]. In other words, the technique of fueling to raise the pedestal pressure does not lead to a degradation of core confinement. Indeed, more detailed analysis confirms that the core thermal transport is in fact modestly reduced. As seen in Figs. 4(c,d), both the ion and electron thermal diffusivities decrease across most the minor radius. 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, as seen in Fig. 4(e), which shows that the time-resolved fluctuation amplitude measured at $\rho \approx 0.8$ decreases as the pedestal increases, with sample spectrum in Fig. 4(f) showing that the fluctuations decrease across the frequency (wavenumber) spectrum, and approach the diagnostic noise floor late in time during the high density, low transport phase. The triggering of a tearing mode that terminates the high confinement phase in these plasmas is likely caused by a reduction in the β_N level for tearing mode onset, resulting also from reduced rotation shear.

Previous studies with the EPED model have indicated that a second region of ELM stable operation with very high pedestals can exist in strongly shaped plasmas, a regime that has been dubbed "Super H-mode" [20]. Typically, EPED will determine a single value for the pedestal height as a function of pedestal density. However, for strongly shaped plasmas, EPED predicts a second possible solution exists above a particular density. The challenge is that a plasma running with fixed density will necessarily encounter the lower pedestal solution first, inhibiting access to the high pedestal pressure predicted by EPED.

The present high density QH-mode plasmas appear to have overcome this limit and accessed the Super H-mode regime as shown in Fig. 5. EPED calculations find two separate regions for ELM stable operation for pedestal densities above approximately 6×10^{19} m^{-3}. By raising the density dynamically once the low collisionality QH-mode edge has formed along the kink-peeling boundary, these plasmas avoid encountering the lower pedestal solution and enter the “channel” of high pressure and density that is otherwise inaccessible. Note that when an ELM is eventually destabilized, there is nearly a factor of two reduction in the pressure with only a modest decrease in density. The ELM therefore “kicks” the plasma out of the second stable region, and at high density the plasma finds itself along the peeling-ballooning boundary at lower pedestal pressure, where it continues to ELM. Hence, the experimental data in Fig. 5 is consistent with the prediction from EPED of a bifurcation in the pedestal height at high density. The associated hysteresis in this process suggests that Super H-mode is likely only sustainable in an ELM-stable plasma such as QH-mode, because once an ELM of sufficient size is triggered to cause the plasma to bifurcate to the lower pedestal state, it may be experimentally challenging to reduce the density sufficiently to get back to the kink-peeling boundary, given the strong fueling required to first access the high density Super H-mode conditions.

This first experimental evidence indicating the existence of a second region of edge stability characterized by enhanced pedestal pressure suggests future research could significantly improve the attractiveness of a fusion power plant. Owing to the prediction that core transport in burning plasmas is very stiff, the ability to access much higher pedestal pressures than typically possible in standard ELMing H-mode conditions could significantly improve the achievable fusion gain of a reactor. These prototype Super H-mode discharges demonstrate the potential to exploit very high pedestals without negatively impacting core confinement, and indeed the EPED predictions presented in Fig. 5 indicate that much higher pedestals may yet still be achievable. Further exploitation of this high pedestal regime could utilize non-axisymmetric fields to enhance rotation shear and EHO robustness [17], and localized deposition of electron cyclotron current drive to control tearing modes, offering a possibility to maximize overall performance significantly beyond what is typically associated with conventional H-mode operation.

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Figures

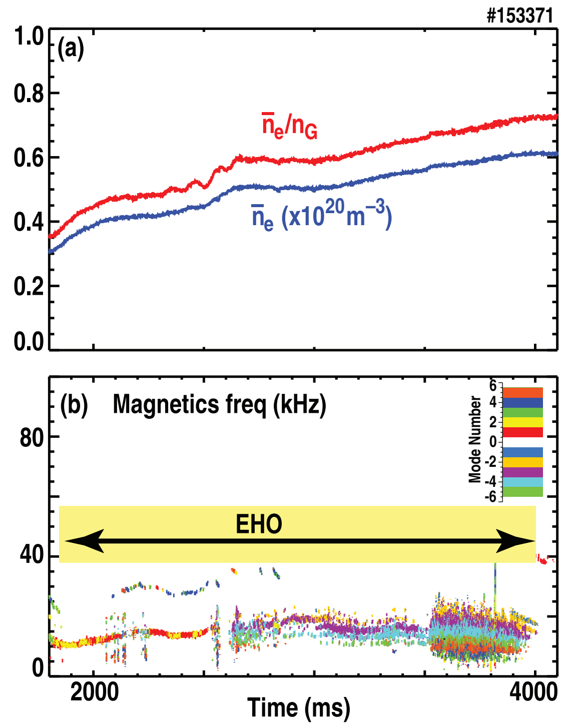
FIG. 1: (a) Evolution of line average density $\bar{n}_e$ and Greenwald fraction $\bar{n}_e/n_G$; and (b) Spectrogram and mode identification from magnetics during strong puffing in QH-mode.

FIG. 2: Maximum attained QH-mode density as a function of the minimum in the triangularity.

FIG. 3: Comparison between experimental measurements and EPED predictions of (a) pedestal height and (b) pedestal width as a function of the pedestal density.

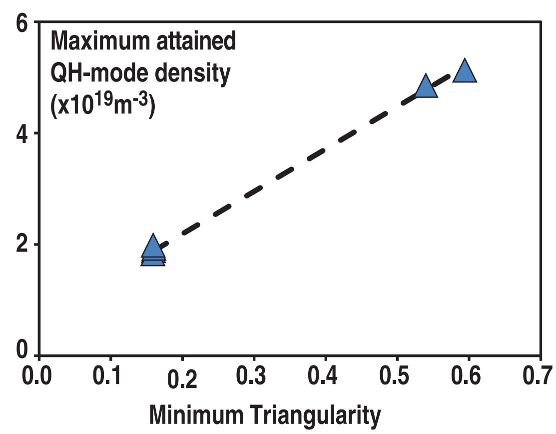
FIG. 4: Evolution of (a) thermal energy confinement time and (b) stored energy during density ramp in QH-mode. The thermal energy confinement increases, coming from a combination of increases in stored energy from both the pedestal and core. Radial profiles of the thermal diffusivities at times $t = 2, 2.2, 2.8, 3.0$ s, averaged ± 0.05 s, for (c) ions, and (d) electrons. (e) Time evolution of normalized density fluctuations from beam emission spectroscopy, and (f) sample density fluctuation power spectra averaged between 2.1 ± 0.1 s and 3.1 ± 0.1 s.

FIG. 5: EPED prediction for ELM stable operating space (blue) as a function of pedestal density, with experimental operating points overlain. Above density $\approx 6 \times 10^{19}$ m^{-3}, there is a bifurcation in the EPED solution, with a high pedestal solution possible (Super H-mode).



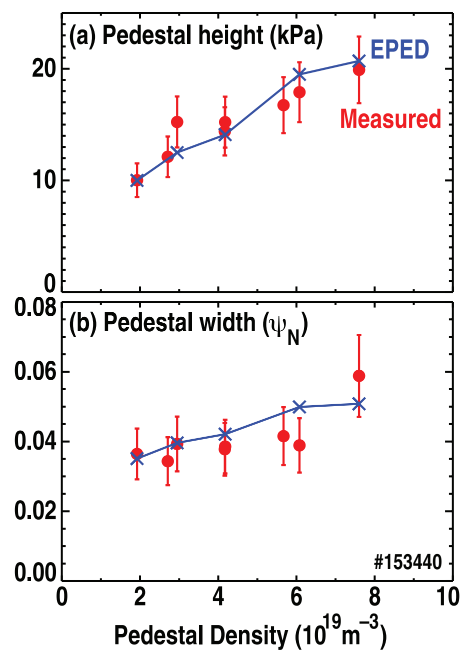
W.M. Solomon Figure 1

Figure 1 20Jun2014

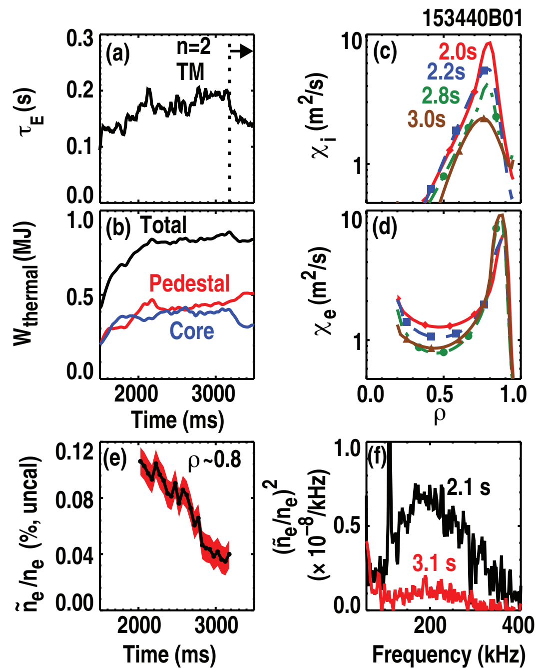


W.M. Solomon Figure 2

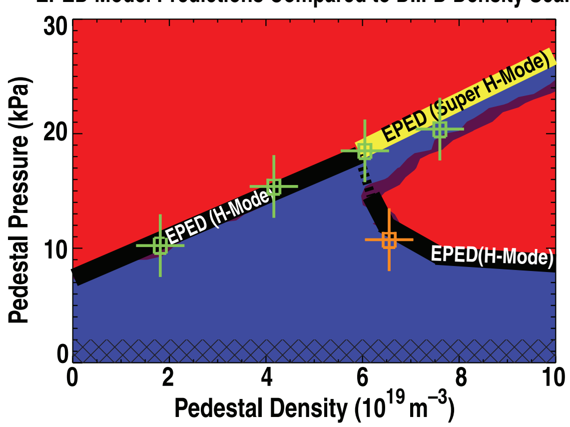
Figure 2 20Jun2014



W.M. Solomon Figure 3



W.M. Solomon Figure 4



W.M. Solomon Figure 5

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