Quiescent H-Mode Plasmas with Strong Edge Rotation in the Cocurrent Direction

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For the first time in any tokamak, quiescent H-mode (QH-mode) plasmas have been created with strong edge rotation in the direction of the plasma current. This confirms the theoretical prediction that the QH mode should exist with either sign of the edge rotation provided the magnitude of the shear in the edge rotation is sufficiently large and demonstrates that counterinjection and counteredge rotation are not essential for the QH mode. Accordingly, the present work demonstrates a substantial broadening of the QH-mode operating space and represents a significant confirmation of the theory.

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Introduction.—With the start of construction of the International Thermonuclear Experimental Reactor (ITER), the worldwide fusion program is looking forward to investigating the physics of burning plasmas, where the dominant plasma heating is provided by fusion reactions. The superior energy confinement time in the H mode makes it the preferred operating mode for ITER [1] and other next step tokamaks. However, edge localized modes (ELMs), which usually occur in the H mode, can have a significant impact on tokamak design and operation. ELMs are MHD modes which result in periodic, rapid expulsion of edge plasma into the divertor; the associated heat and particle pulse can lead to rapid erosion of the divertor plates [2]. The allowable size of the ELM pulse has recently been reassessed [2], and significant changes have been made to the ITER design to meet these requirements. On the other hand, the extra particle transport produced by ELMs is beneficial because it aids in impurity control and helium ash removal [1,3]. Because of the detrimental effects of ELMs, a major effort is underway to develop techniques which either limit the size of the ELM heat pulse (e.g., pellet pacing [4]) or eliminate the ELMs altogether while still retaining the extra particle transport needed for impurity and helium ash control [5–8].

Quiescent H-mode (QH-mode) [7,8] plasmas provide ELM-free operation at constant density and radiated power, good edge particle exhaust, and the extra energy confinement given by the H-mode edge pedestal. The QH mode is different than the standard ELM-free H mode, where the density and radiated power rise monotonically. An edge electromagnetic mode, the edge harmonic oscillation (EHO), provides extra edge particle transport that, time-averaged, exceeds that produced by the ELMs [9] and allows the constant density operation [9–12]. The EHO is generated by the plasma itself and, hence, the QH mode does not require the additional coils needed for ELM suppression using resonant magnetic perturbations [5,6]. In addition, unlike the enhanced D_α H mode [13], the QH mode has no known upper pedestal temperature limit; QH modes have been seen in DIII-D at input powers up to those required to reach the core beta limits (~15 MW) [9]. The QH mode would allow H-mode levels of temperature and fusion reactivity in future devices.

The QH mode was originally discovered in DIII-D in discharges with the neutral beam injection (NBI) in the direction opposite to the plasma current (counterinjection) [8,9]. It has subsequently been studied in ASDEX-U [14,15], JET [15], and JT-60U [16,17]. In all those cases, the edge plasma rotation was in the direction opposite to the plasma current (counterrotation). Previous experiments on JT-60U which produced the QH mode with net co-NBI actually exhibited counterrotation in the edge pedestal region, possibly due to edge ion loss caused by toroidal field ripple [16,17]. Edge counterrotation in previous QH-mode experiments lead to the speculation that counterrotation was essential for the QH mode. If this were true, it would pose a problem for the use of the QH mode in next step devices, since there is a desire to use cocurrent neutral beam current drive (NBCD) to shape the radial profile of the plasma current in these devices. A requirement for counterrotation would also contradict a recent theory of the QH mode [12], which predicts that the QH mode is possible with either sign of the edge rotation provided the shear in that rotation is large enough.

The results presented in this Letter demonstrate that the QH mode is possible with 100% coinjection and with strong edge corotation. This confirms the theoretical prediction that the QH mode is possible with either sign of the edge rotation [12]. Accordingly, the results presented here demonstrate a substantial broadening of the QH-mode operating space and represent a significant test of the theory.

Peeling-ballooning mode stability theory and the EHO.—The theory of the stability of the edge peeling-ballooning (kink) modes, embodied, for example, in the ELITE code [18,19], allows us to understand a number of features of the QH mode [11]. As is indicated in Fig. 1, the peeling-ballooning modes are driven unstable by edge pressure gradient and by edge current density. ELITE calculations, illustrated in Fig. 1, indicate that the most unstable modes along the peeling boundary have toroidal mode numbers $n < 5$. As edge density and collisionality increase, the most unstable modes move to higher $n > 25$ along the ballooning boundary. All QH modes analyzed to date show that ELM-free operation is consistent with the stability predictions of the theory, with the operating points on or below the peeling boundary within the experimental error bars [9–12].

The peeling-ballooning mode stability theory has recently been extended to provide a semiquantitative theory of the EHO [12]. The EHO is a nonsinusoidal, electromagnetic, edge-localized oscillation which typically exhibits one dominant toroidal mode number n (typically 1–3) and harmonics (n up to 8) [9].

Although the dominant instability drives are the edge pressure gradient and edge current density [12,18,19], the edge rotation gradient can also affect peeling-ballooning modes [12]. As is shown in Fig. 2, low n modes are further destabilized by edge rotational shear. The theory posits that the EHO is a low n peeling mode driven unstable by rotational shear at edge conditions slightly below the ELM stability limit in the absence of rotation. As the mode grows to finite amplitude, its magnetic fields interact with the vacuum vessel wall, slowing the rotation, decreasing the rotational shear, and, hence, reducing the drive for the mode; this provides one mechanism for the mode to saturate at finite amplitude. Experimentally, we see a decrease in edge rotation and an increase in edge particle transport whenever the EHO starts and grows to finite amplitude [9]. The increased particle transport also leads to reduced edge density gradients, which in turn reduce the edge bootstrap current, also reducing the drive for the mode. This theory allows us to quantitatively calculate the edge stability and qualitatively understand the characteristics of the EHO; however, a more complete theory is still needed to explain how the EHO enhances the edge particle transport.

The theory states that the stability depends only on the magnitude of the rotation shear, not the sign. Accordingly, the theory predicts that the QH mode should occur for both co- and counterplasma rotation.

Coinjected QH mode.—We have now created QH-mode plasmas with strong edge corotation in discharges with 100% coinjection. Figure 3 shows that these shots have all the usual QH-mode features: (1) ELM-free operation with constant density and radiated power, (2) H-mode level of confinement including the usual H-mode edge pedestal, and (3) enhanced edge particle transport due to the EHO. This enhanced particle transport is demonstrated both by the constant density operation and by the increase in the divertor D_α baseline seen in Fig. 3(b) when the EHO amplitude [Fig. 3(c)] increases. The operational recipe for these plasmas is quite similar to that used for QH modes with counterinjection. Low-density operation using divertor cryopumping was one key factor. A second technique employed was feedback control of the neutral beam power to hold normalized β_N constant at 1.7 after the L-to-H transition. Operationally, this recipe produced large toroidal rotation speeds in the edge pedestal of up to 200 km/s.

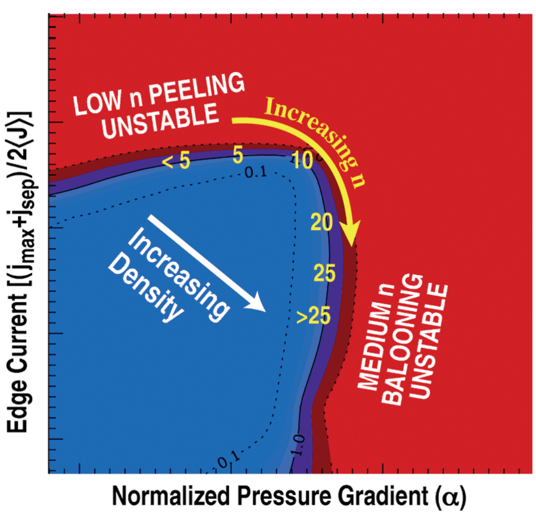

FIG. 1 (color). Simplified diagram of the ELITE results for the peeling-ballooning mode stability of the edge plasma in an H-mode discharge. The horizontal axis is the MHD ballooning parameter α, which is proportional to the peak pressure gradient in the edge pedestal; for the exact definition, see Ref. [20]. The vertical axis is the normalized edge current; see Ref. [12]. n is the toroidal mode number of the peeling-ballooning mode.

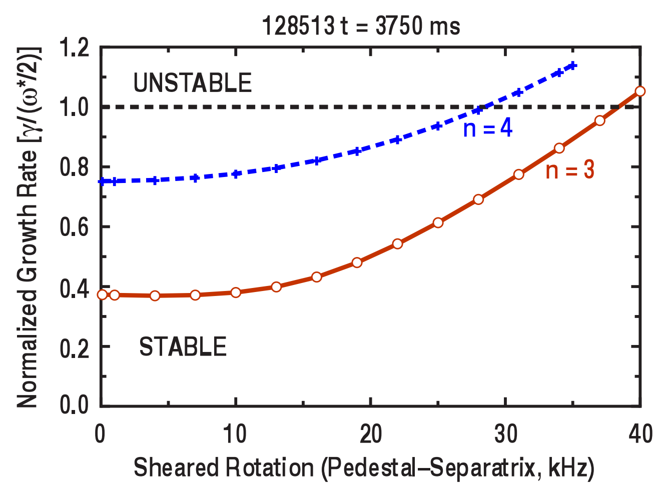

FIG. 2 (color online). Calculated growth rate of the peeling-ballooning modes γ normalized to half the diamagnetic frequency ω_* versus the difference in the plasma toroidal angular rotation speed at the top of the pedestal and on the separatrix. This difference is proportional to the edge rotational shear. Modes with various toroidal mode number n become increasingly unstable as the edge rotational shear increases.

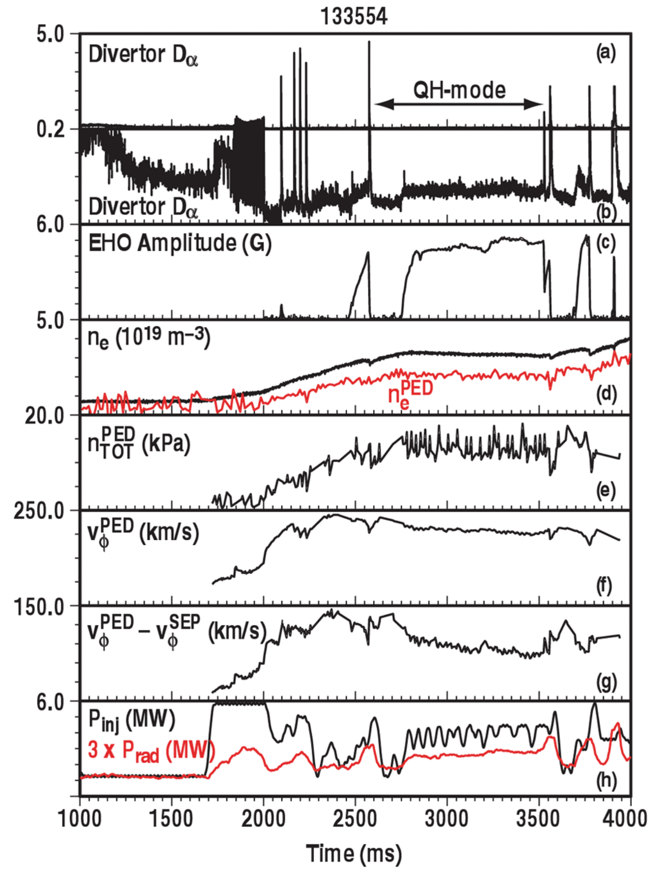

FIG. 3 (color). Time history of a coinjected QH-mode plasma. (a) and (b) Divertor D_α emission on two different vertical scales, (c) amplitude of the fluctuating magnetic field associated with the EHO, (d) line averaged (black) and pedestal density (red), (e) total plasma pressure at the top of the H-mode edge pedestal, (f) toroidal rotation speed of the plasma at the top of the edge pedestal, (g) difference between the pedestal and separatrix toroidal rotation speeds, and (h) neutral beam input power (black) and 3 times the total radiated power from the plasma (red). The plasma current is 1.1 MA, and the toroidal field is 2.15 T with the ion ∇B drift direction towards the X point of the divertor discharge.

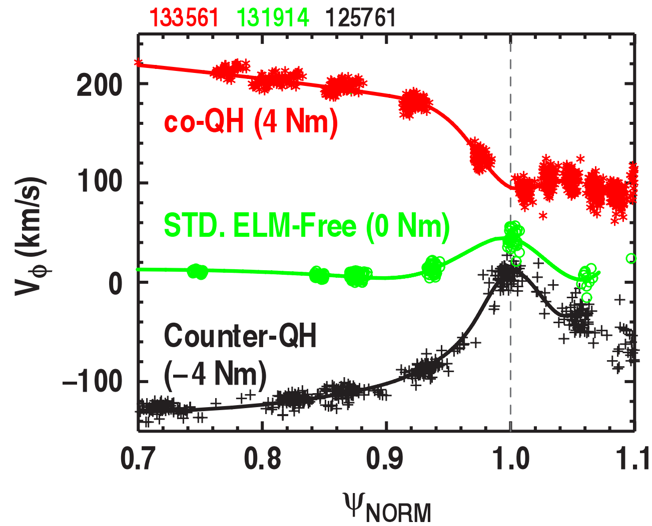

FIG. 4 (color online). Edge rotation profile for three discharges with total neutral beam input power in the 4–5 MW range. The profile is plotted as a function of the normalized poloidal flux function. The counter-QH (black) and co-QH (red) curves have a torque input of with a magnitude of 4 N m while the standard ELM-free discharge has 0 N m input torque.

The rotation speed is approximately twice that seen in counterinjected QH-mode plasmas of similar shape and with similar torque input.

The magnitude of the edge rotation shear in Fig. 4 is similar for both the co- and counter-NBI QH-mode plasmas. This is consistent with the theory of the EHO discussed earlier [12]. The magnitude of the edge rotational shear is significantly lower for a comparison shot with balanced beam injection and zero net torque input. There is no EHO seen at this torque level; the rotation measurement is from a time when the plasma is in the standard ELM-free state. The absence of the EHO in this case with low rotation shear is also consistent with the theory [12].

At present, co-NBI QH modes lasting up to about 1 s have been seen on DIII-D. The termination of the QH mode may be due to the decay of the edge rotation shear. As is shown in Fig. 3(g), the difference between the pedestal rotation and the separatrix rotation decreases slowly with time during the QH-mode phase. The power and torque input used in the QH-mode phase of these discharges is low when compared to that usually used in counter-NBI QH modes.

The first corotating QH mode seen on DIII-D was discovered serendipitously during an experiment run for another purpose. The results reported here come from a dedicated experiment which began from the plasma conditions in that serendipitous case. This dedicated experiment showed that co-NBI QH mode could be reproducibly obtained. As can be seen in Fig. 5(b), within error bars, these corotating QH modes also operate near the peeling stability boundary, demonstrating agreement between the theoretically predicted stability boundary and the experimentally determined operating point. This lower single-null shape actually has reasonably good edge stability properties, exhibiting a normalized edge p' value and a normalized current density value both about a factor of 2 better than in counterinjected QH-mode plasmas in the single-null shape [11]. At present, we do not completely understand why this particular shape is as stable as it is. The significant upper triangularity of this lower single-null shape may contribute to the improved stability.

Given the lengthy history of H-mode operation with co-neutral beam injection, a key question is why QH-mode operation with coinjection was not discovered sooner. We speculate that the combination of low-density, cryopumped operation plus feedback control of the neutral beams allows the plasma to reach a state that is not readily accessible otherwise. Another example of such a situation where

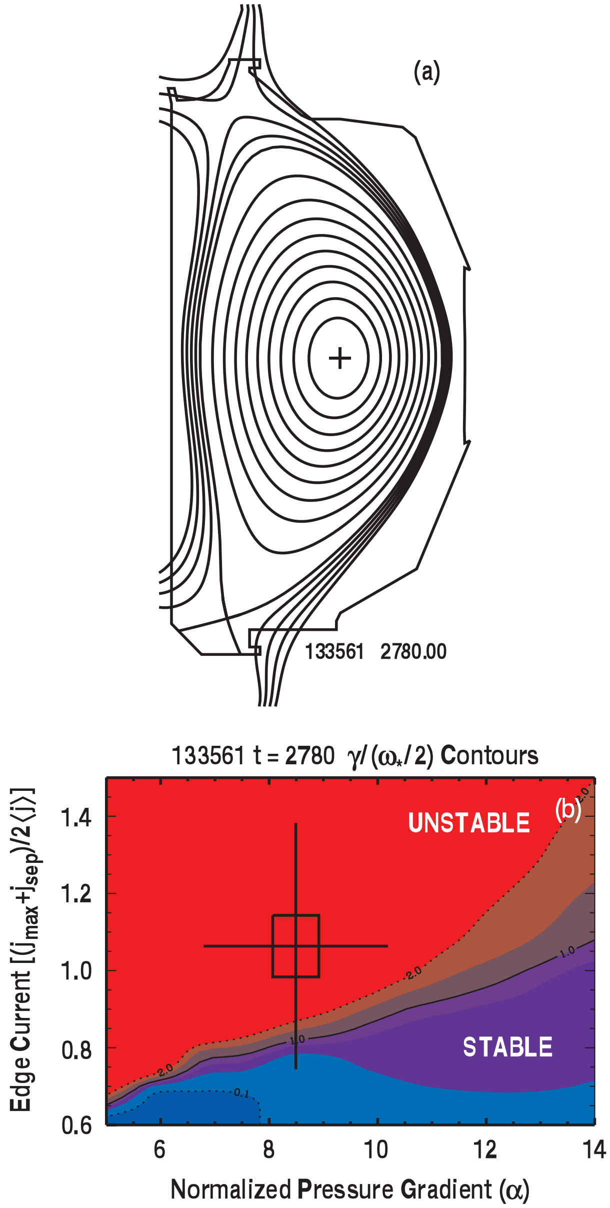

FIG. 5 (color). (a) Plot of shape of the coinjected QH-mode plasma shown in Fig. 3. (b) ELITE calculation of peeling-ballooning mode stability results for this plasma (color contours) and the actual operating point of this plasma. Note that the operating point is within error bars of the stability boundary.

beam feedback leads to a new operating point is the hybrid discharges in DIII-D [21]. In these shots, feedback control of the beam waveform to rapidly reach and then maintain a specified stored energy allows the creation of a discharge with a core 3/2 or 4/3 tearing mode which alters the current profile and suppresses the sawtooth oscillations. In both the hybrid and co-NBI QH-mode cases, we see situations where feedback control of the beam power to control the plasma stored energy leads to a stationary state with a finite amplitude MHD mode where the plasma operating point remains away from the boundary for an explosively growing instability (either the sawtooth or the ELM).

An additional factor allowing the co-NBI QH-mode operation may be the good edge stability properties of the plasma shape shown in Fig. 5(a). QH-mode operation requires the achievement of a transport steady state at edge conditions where the ELMs are stable. If this ELM stable region is broader, then less additional transport is needed to keep the plasma edge parameters within the stable region.

Conclusion.—For the first time in any tokamak, we have created the QH mode in plasmas with 100% coinjection and with strong edge corotation. The existence of the QH mode with strong edge corotation is a confirmation of the theoretical prediction that the QH mode should exist with either sign of the edge rotation provided the magnitude of the shear in the edge rotation is sufficiently large. The agreement of the experimental operating point with the stability boundary shown in Fig. 5(b) extends the previous detailed confirmation of the theory [9–12] to corotating QH-mode plasmas. In addition, the existence of the QH mode with edge corotation demonstrates that counter-NBI and counteredge rotation are not essential conditions for the QH mode. Finally, these results show that the same neutral beam injection direction can be used for NBCD and the QH mode. Accordingly, the present work demonstrates a substantial broadening of the QH-mode operating space and represents a significant confirmation of the theory.

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