Advances Toward QH-mode Viability for ELM-free Operation in ITER

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Abstract. The application of static, non-axisymmetric, nonresonant magnetic fields (NRMFs) to high beta DIII-D plasmas has allowed sustained operation with a quiescent H-mode (QH-mode) edge and both toroidal rotation and neutral beam injected torque near zero. Previous studies have shown that QH-mode operation can be accessed only if sufficient radial shear in the plasma flow is produced near the plasma edge. In past experiments, this flow shear was produced using neutral beam injection (NBI) to provide toroidal torque. In recent experiments, this torque was nearly completely replaced by the torque from applied NRMFs. The application of the NRMFs does not degrade the global energy confinement of the plasma. Conversely, the experiments show that the energy confinement quality increases at low plasma rotation. Furthermore, the NRMF torque increases plasma resilience to locked modes at low rotation. These results open a path toward QH-mode utilization as an ELM-stable H-mode in the self-heated burning plasma scenario, where toroidal momentum input from NBI may be small or absent.

1. Introduction

One of the critical issues on the tokamak path to nuclear fusion as a source of electricity is realizing a high confinement mode of plasma operation (H-mode) without the large, pulsed heat loads to the wall that usually result from instabilities driven by the high pressure gradient of the H-mode edge pedestal. These periodic heat and particle ejections from the plasma core are caused by magnetohydrodynamic instabilities known as edge-localized modes (ELMs). While they might provide sufficient edge particle loss to prevent helium ash accumulation in a burning plasma core, they also severely limit the lifetime of the divertor, a key particle and impurity control component of a tokamak. The size of ELMs can be reduced by increasing their frequency, which could be accomplished by ELM triggering using pellet injection [1] or using magnetic “kicks” [2]. Alternatively, ELMs can be completely eliminated, albeit under narrow parameter ranges, using static non-axisymmetric fields which are resonant with the equilibrium magnetic field near the plasma edge [3]. These ELM control approaches still need to be demonstrated under burning plasma conditions (e.g., low input torque, low collisionality).

Another possibility would be operation in a regime that exhibits the high confinement of H-mode without ELMs. Such a regime, the quiescent H-mode (QH-mode), [4] is ELM-stable as a result of increased edge particle transport due to an edge harmonic oscillation (EHO) [5], a benign rotating edge MHD mode. The additional particle transport driven by the EHO allows the plasma edge to reach a transport equilibrium at edge pressures and current densities below the ELM stability boundary [4,6]. Theory indicates the EHO is a saturated kink-peeling mode driven unstable by edge rotational shear at edge parameters near but below the ELM stability boundary in the absence of rotation [6]. This theory is independent of the sign of the rotational shear, which is consistent with experimental results [7] that QH-mode can be produced with edge rotation either in the direction of the plasma current or counter to it. In past experiments, this edge flow shear was produced using neutral beam injection (NBI) to provide toroidal torque. However, a self-heating fusion plasma will likely have near zero NBI torque.

This paper reports on the first demonstration in a tokamak of the use of non-axisymmetric fields to achieve the ELM-stable regime of quiescent H-mode (QH-mode), in the reactor-relevant regime of low-collisionality plasmas with significant normalized pressure and zero NBI torque [8]. Recent theoretical and experimental work has brought significant advances in the understanding of the interaction of static non-axisymmetric fields with a rotating high beta plasma. When a non-axisymmetric nonresonant magnetic field (NRMF) is applied to a near-stationary plasma, the toroidal rotation is accelerated toward a neoclassical "offset" rotation rate, which is in the direction opposite to the plasma current (counter-I_p) [9,10]. This magnetically driven torque provides a new knob to control the plasma rotation, and can be utilized to provide a counter-rotation profile that is suitable for QH-mode operation with no net NBI torque. In the experiments described in this paper, the NBI torque was completely replaced by the torque from applied NRMFs.

The remainder of the paper is organized as follows: Section II elucidates the torque balance in these NRMF-assisted QH-modes, showing how the NRMF torque can replace the NBI torque in providing the edge rotation shear needed for QH-mode operation. Sections III and IV describe the effects of the NRMF respectively on confinement and on stability. Section V illustrates how these experiments have also allowed us to discriminate which type of rotation is important for maintaining the QH-mode edge. Section VI summarizes the results and discusses future work.

2. NRMF-Assisted QH-mode

Non-axisymmetric, mostly nonresonant magnetic fields (NRMFs) of toroidal mode number $n = 3$ can be applied to DIII-D plasmas using the I-coil (see Fig. 1), a set of 12 picture-frame coils distributed toroidally and poloidally inside the vessel [11]. The experiments described in this paper used the largest perturbation deliverable by the I-coil, in which the largest single poloidal harmonic with $n = 3$ has a flux surface-averaged amplitude $\delta B \sim$ 12 G at the plasma surface ($\delta B/B \sim 0.6\times10^{-3}$), ignoring any plasma response. To maximize the perturbation effect, the toroidal phase of the I-coil field is chosen so that the external $n = 3$ field adds to a known, small $n = 3$ intrinsic error field. Target discharges are QH-mode plasmas with lower single null divertor cross-section shape, reactor-relevant pedestal collisionality, $\nu_e^* \sim 0.1$, monotonic safety-factor profile with $q \sim 1$ on axis and value at the 95% flux surface (q_{95}) of ~5.0, and β_N in the range 1.8 to 2.1 [$\beta_N = \beta/(I_p/aB)$ is the normalized β, where $\beta = \langle p\rangle/(B^2/2\mu_0)$ is the dimensionless plasma pressure, I_p the toroidal plasma current, a the plasma minor radius, and B the magnetic field strength]. The plasma β_N is kept constant via feedback control of the NBI power. The feedback system can also control the injected NBI torque, $T_{\rm NBI}$, by changing the mix of co- and counter-injected beams. $T_{\rm NBI}$ and plasma rotation are defined positive in the co-I_p direction. The plasma rotation is measured by charge exchange spectroscopy of the carbon impurity ion rotation.

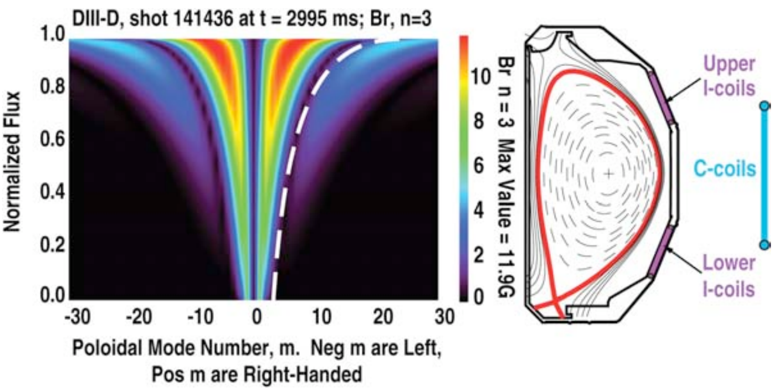

FIG. 1. (a) Contour plot of the Fourier poloidal harmonic amplitudes of the $n = 3$ radial magnetic field perturbation applied by the I-coil (I = 6.5 kA), shown as a function of poloidal mode number m and minor radius. The loci of $m = nq$ resonance, indicated by the white dashed line, lie in a valley of field amplitude (i.e. the perturbation is almost purely nonresonant). (b) ITER-similar cross section of the target plasma for the $n = 3$ field application, also indicating the I-coil and C-coil locations.

The first evidence that static, $n=3$ NRMFs can maintain QH-mode with lower NBI torque than required without NRMFs is shown in Fig. 2. The QH-mode regime is ELM-stable as a result of increased edge particle transport due to a benign rotating edge MHD mode called the edge harmonic oscillation (EHO) [5]. Theory and experiments indicate that large edge rotational shear is a key requirement for existence of the EHO [6,7]. Until recently, tokamak experiments relied on momentum injection from neutral beams to achieve the rotation shear required for access to QH-mode. For both plasma discharges in this figure, T_{NBI} is slowly ramped towards zero from ~ –6 Nm at 2.2 s, at nearly constant injected power. In the discharge without the n = 3 NRMF, the toroidal rotation drops quickly with the NBI torque, and reaches zero by T_{NBI} ~ –2.5 Nm, at which point first QH-mode is lost, then a locked mode spoils the confinement. The observation of zero rotation with finite NBI torque is consistent with an effective “intrinsic” (self-generated) co-torque that balances the NBI torque at this point. The magnitude of T_{Intr} ~ 2.5 Nm is consistent with the empirical proportionality to the stored energy, “Rice scaling” [12], calculated for DIII-D discharges [13]. In contrast, in the similar discharge with a constant n = 3 NRMF applied throughout the time range shown, a larger counter-rotation is obtained for the same NBI torque, and the QH-mode is maintained until $T_{\mathrm{NBI}} \sim 0$.

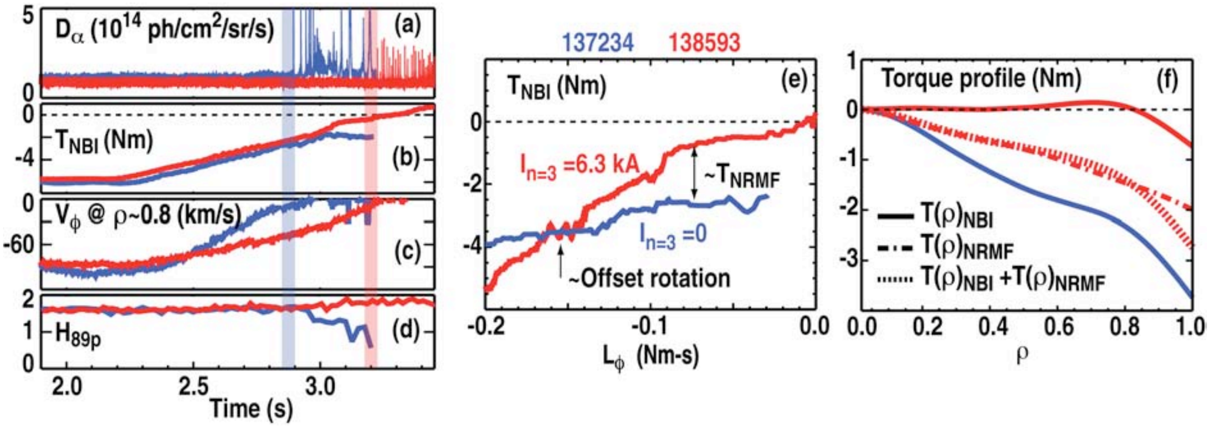

FIG. 2. Comparison of NBI torque rampdown discharges with constant NRMF applied (red traces, 6.3 kA of $n=3$ I-coil current) and with no NRMF (blue traces). (a) Time histories of D_α light, showing QH-mode regime when bursting behavior (from ELMs) is absent; (b) NBI torque; (c) plasma toroidal rotation at $\rho \sim 0.8$; (d) energy confinement quality. (e) Discharge trajectories in the plane of NBI torque versus total toroidal angular momentum. (f) Profiles of integrated torque density versus normalized minor radius calculated just before end of QH-mode phase [times indicated by vertical bands in (a)-(d)]. Only four curves are shown in (f) since $T(\rho)_{\mathrm{NRMF}} = 0$ for the blue case.

Larger counter-rotation for the same NBI torque is expected based on recent theoretical [9] and experimental [10] work showing that, at slow counter-rotation, static NRMFs can accelerate a plasma. The torque driven by the NRMF tends to drag the plasma toward a neoclassical offset rotation velocity in the counter-I_p direction, $T_{\mathrm{NRMF}} \propto -(V_\phi - V_\phi^0)$, with V_ϕ^0 the offset rotation. A simple comparison in Fig. 2(e) of the T_{NBI} required to obtain the same angular momentum in similar discharges with and without NRMF, reveals the approximate magnitude of the NRMF torque, assuming the same intrinsic torque and angular momentum confinement time, τ_ϕ, in both discharges and neglecting dL_ϕ/dt in the torque balance equation (L_ϕ is the total toroidal angular momentum): $T_{\mathrm{NBI}} + T_{\mathrm{NRMF}} + T_{\mathrm{Intr}} - L_\phi/\tau_\phi = dL_\phi/dt$. The observation that the NRMF torque increases as the rotation approaches zero is consistent with the offset linear dependence of T_{NRMF} on the rotation. However, a nonlinear effect may be playing an important role here. According to neoclassical theory, at this low rotation the NRMF torque is amplified by entering a regime where the radial electric field vanishes, leading to “superbanana” particles with enhanced radial fluxes, which in turn exert a larger toroidal torque on the plasma [14]. Measurements of the dependence of this torque on the plasma velocity have shown that a peak in the torque exists at very low plasma rotation, and that this peak is found to occur where the radial electric field is small, as predicted by theory.

A more accurate transport analysis of the angular momentum balance in similar discharges with and without NRMF shows that the NRMF torque nearly completely compensates for the lower NBI torque in the discharge with the $n = 3$ NRMF applied. Described in Ref. [13], this transport analysis technique yields the profiles of the integrated NRMF and NBI torque densities shown in Fig. 2(f), confirming the simpler analysis. The figure compares integrated torque profiles at times just before the QH-mode phase ends in both discharges. Note that, from the momentum balance equation considering only diffusive transport, the rotation shear at the plasma edge depends on the integral of the torque density up to the edge, not on the local torque density distribution. Since a large edge rotation shear is a key condition for QH-mode, this analysis suggests that the $n = 3$ NRMF maintains QH-mode at lower NBI torque mostly by helping provide a sufficient total torque on the plasma. Indeed, the NRMF torque does not exactly compensate for the lower NBI torque, therefore secondary effects may be at play. These may also be reflected in the observation that key requirement for QH-mode operation seems to be the shear in the edge toroidal rotation driven by the radial electric field ($\omega_E = E_r / R B_\theta$), not the rotation of the carbon impurity ion, as will be discussed in Section IV.

3. NRMF Effects on Confinement

Application of the NRMF does not cause adverse impact on the global energy confinement. The global confinement quality, as measured by the confinement enhancement factor with respect to the ITER-89P L-mode confinement scaling [15], is unchanged during the QH-mode phase with or without the NRMF, as shown in Fig. 2(d). Figure 3(c,d) shows a comparison of the profiles of electron density and ion temperature before and during the NRMF application. After the NRMF turn-on, the density is reduced everywhere and the core ion temperature is increased. The electron temperature (not shown) is nearly unchanged. The density pump-out is an effect of non-axisymmetric field application observed also in other tokamaks [16], and whose physics explanation is under active investigation. Again, the confinement quality is unchanged during the QH-mode phase with or without the NRMF, other than a small dip immediately following the NRMF onset. This dip corresponds to a temporary return to ELMing behavior, in some cases limited to the occurrence of one ELM.

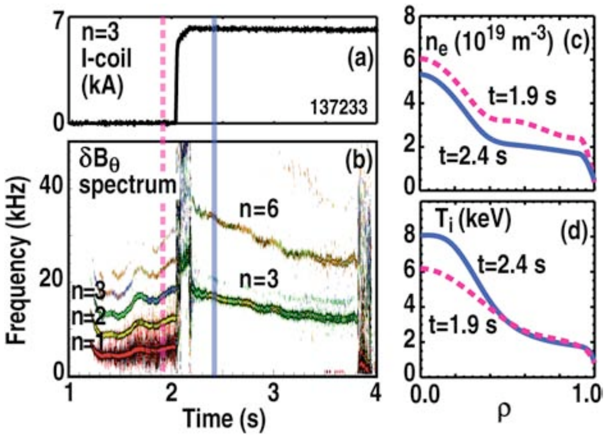

FIG. 3. (a) I-coil current generating the $n = 3$ NRMF; (b) Colored contour plot of the toroidal mode number, n, spectrum of magnetic fluctuations versus frequency and time. Vertical lines indicate times before and after the NRMF application, for comparison of radial profiles of (c) electron density and (d) ion temperature.

It is consistently observed that the application of the $n = 3$ NRMF changes the character of the EHO. This is shown by the spectrum of measured magnetic fluctuations shown in Fig. 3. Before the NRMF application, the discharge is in QH-mode with an EHO having a typical spectrum with dominant toroidal mode number $n = 1$ and several harmonics. During the NRMF application, once the discharge goes back into QH-mode after a brief ELMing phase, the magnetic spectrum of the EHO has changed to one with dominant $n = 3$ and harmonics. The cause of this behavior is under investigation. At present, it is speculated that the EHO structure change may not be directly related to the mode number of the applied NRMF, rather to the effect of the NRMF on the equilibrium profiles and hence on the MHD stability of the edge modes.

The global confinement quality of these NRMF-assisted QH-mode discharges is found to increase at lower net NBI torque and at higher β_N. Furthermore, lower net NBI counter torque is required to maintain QH-mode at higher β_N. This behavior is documented in Fig. 4. Here, a comparison of discharges with nearly identical NBI torque evolution but different requests to the β_N feedback control (discharges 138604 and 138605, with $|T_{\rm NBI}|$ ramped down to -1 Nm) shows that the discharge with higher β_N achieves higher energy confinement quality at low $|T_{\rm NBI}|$. The improved confinement correlates with the observation of reduced turbulence levels from Doppler Backscattering measurements [17] of fluctuations with poloidal wavenumber $k_\theta \sim$ 3.9 cm^{-1} in the electron density inboard of the H-mode pedestal [$k_\theta \rho_s \sim 1$ with $\rho_s = c_s m_i / e B_T$, $c_s = (kT_e/m_i)^{1/2}$]. This wavenumber is often associated with trapped electron mode instabilities. Radial profiles of density fluctuations before and after $|T_{\rm NBI}|$ ramp-down are shown in Fig. 4(f,g). The rotation also decreases substantially at lower $|T_{\rm NBI}|$, as shown in Fig. 4(e). At lower β_N the measured fluctuation level does not change when the rotation is decreased. In contrast, at higher β_N fluctuations decrease substantially at lower rotation. These observations suggest that the improved confinement with lower rotation may not be related to sheared flow stabilization of turbulence. More analysis is needed to clarify these surprising observations.

Furthermore at higher β_N, a lower net NBI counter torque is sufficient to maintain QH-mode. Figure 4 shows the lower β_N discharge goes back into an ELMing regime as the torque is lowered to –1 Nm, while at higher β_N the QH-mode is maintained with the same NBI counter torque. The observation of lower NBI torque requirement for sustained QH-mode at higher β_N is consistent with the documented greater NRMF torque at higher β_N [18].

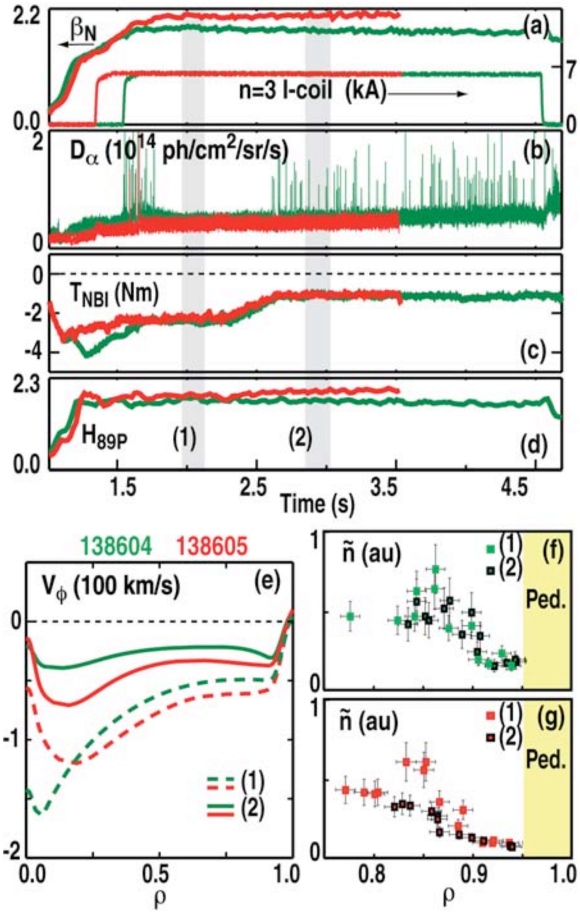

FIG. 4. Effects of NBI torque ramp down in discharges with different values of β_N. The discharge in red (138605) is terminated early by a fault of the plasma control system. Time histories of: (a) β_N, I-coil current; (b) D_α light; (c) NBI torque; (d) confinement quality. Shaded vertical bands labeled (1) and (2) indicate time ranges relevant to the next panels. (e) Radial profiles of toroidal plasma rotation averaged over the time ranges of turbulence measurement analysis, (1) and (2). Radial profiles of relative density fluctuation level measured by Doppler backscattering at high and low rotation in (f) discharge with lower β, and (g) discharge with higher β.

4. NRMF Effects on Stability

The DIII-D discharge shown in Fig. 5 demonstrates that QH-mode can be maintained down to zero-net NBI counter torque when the $n = 3$ NRMF torque from the I-coil is augmented with an $n = 3$ field applied by the C-coil. The C-coil, a non-axisymmetric coil set external to the vessel and mainly utilized for $n = 1$ error field correction in these experiments, was used to increase the vacuum $n = 3$ field by ~50% at the plasma boundary in this discharge.

However, the application of $n = 3$ NRMFs does more than just expand the QH-mode operating space to a zero-net NBI torque regime. The discharge of Fig. 5 shows high beta and high confinement operation of a plasma with very low density (line averaged density <2.5x10^{19} m^{-3}), and very low rotation (~0 at the $q = 2$ surface), i.e. conditions that typically lead to catastrophic locked modes.

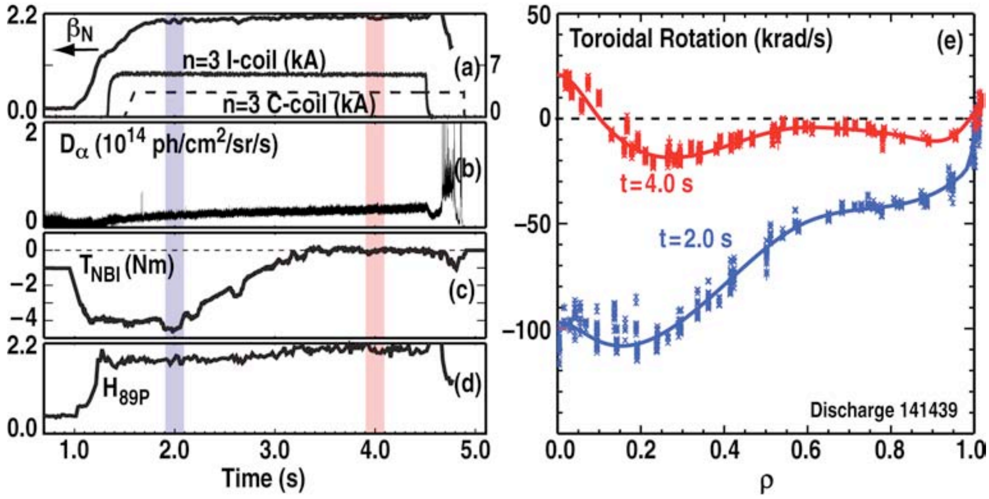

FIG. 5. Demonstration of sustained QH-mode with zero net NBI torque. Time histories of: (a) β_N, I-coil and C-coil currents; (b) D_α light; (c) NBI torque; (d) confinement quality. Shaded vertical bands indicate time ranges for toroidal rotation profiles shown in (e), before (blue) and after (red) the NBI torque is removed.

The improvement of stability against locked modes in plasmas with zero-net or small counter-rotation is due to two separate NRMF physics mechanisms. Generally, a locked mode occurs when plasma rotation at a rational surface is no longer sufficient to shield a resonant error field. Without rotational shielding, the error field can easily open a magnetic island and, at finite beta, destabilize a metastable neoclassical tearing mode. Figure 2 showed that, by driving a counter torque, the application of NRMFs maintains counter rotation and avoids ELMs and locked modes as the NBI torque is reduced. A second mechanism is at work in the case shown in Fig. 6. Here, two similar discharges are compared, both with applied $n = 3$ NRMF from the I-coil and ramp down of the NBI torque magnitude. Removing the $n = 3$ field at low torque in one discharge (138608) leads promptly to an $n = 1$ locked mode instability, while in the discharge with continued NRMF application (138611), stability is maintained even with lower NBI torque. One possible explanation is that a small magnetic island is already formed when the rotation comes down near zero while the $n = 3$ field is applied, and that the island may not grow as long as the $n = 3$ field is applied because of a mechanism that was originally proposed in [19]. In this hypothesis, the locally nonresonant $n = 3$ helical field enhances the perpendicular transport across the island, therefore weakening the helically perturbed bootstrap destabilization of the NTM. When

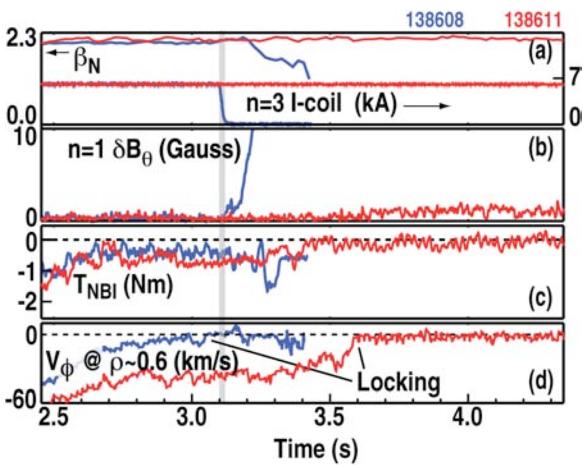

FIG. 6. Comparison of discharges with and without removal of the $n = 3$ NRMF during phase of low NBI torque. Time histories of: (a) β_N and I-coil current; (b) $n = 1$ locked mode detector signal; (c) NBI torque; and (d) toroidal plasma rotation at the approximate location of the $q = 2$ surface.

the helical field is removed, the NTM suppression mechanism is removed as well, and the island starts to grow. This hypothesis is supported by the clear observation of locked rotation without mode growth in the stable discharge (138611). The rotation near the q=2 surface in this discharge can be seen to lock to zero at t=3.6 s, and remains firmly locked implying the presence of a small, stationary magnetic island. The island must be small since there is no sign of confinement degradation and a perturbation in the magnetic sensors is only barely observable. With the large $n = 3$ NRMF applied, the m/n=2/1 island remains stable for several energy confinement times, and is destabilized only when the $n = 1$ error field correction is ramped down near the end of the discharge.

The hypothesis of NTM inhibition by an externally applied helical field had been tested successfully in previous DIII-D experiments [20]. However, in those experiments the initial plasma rotation was large and co-directed. The application of an $n = 3$ field in that case leads to rotation slowing down toward zero and reduction in confinement. In the new experiments reported here, the negative effects of the applied helical field are eliminated or reversed. In the counter-rotating plasma regime the application of an $n = 3$ field tends to maintain a large rotation (close to the neoclassical offset). When the rotation is forcibly reduced by changing the neutral beam torque, the confinement increases.

5. Test of QH-mode Requirements

Because the theory of the EHO is based on single fluid MHD, it makes no distinction between the fluid toroidal rotation and $\omega_E = E_r/RB_\theta$, the toroidal rotation driven by the radial electric field. These recent DIII-D experiments show that the shear in $\omega_E = E_r/RB_\theta$ is the important rotational shear for QH-mode operation, rather than the shear in the measured rotation of the impurity ions (commonly assumed as a proxy for the fluid rotation). The rotation profiles measured at low NBI torque show that a large shear in the edge velocity of carbon impurity ions is not required to sustain QH-mode with NRMFs. The correlation between QH-mode edge and large shear in the edge ω_E rotation holds well in the cases analyzed so far, when the shear is evaluated across the outer half of the H-mode pedestal (last 2% to 3% of the poloidal flux). Figure 7 shows a plot of the difference in C ion angular rotation speed $\Omega = V_\phi/R$ between the H-mode pedestal midpoint and the boundary ($\Delta\Omega$) versus the similarly evaluated difference in the ω_E rotation ($\Delta\omega_E$), for a database of discharges with different edge characteristics. In order to compare discharges at different conditions, the rotation is normalized to the local Alfven frequency, which is the relevant MHD frequency. A boundary near $\Delta\omega_E/\omega_A \sim 7‰$ emerges between discharges that exhibit a QH-mode edge and discharges that are ELMing or standard ELM-free H-modes. These results suggest that the important rotation shear for QH-mode access is the ω_E rotation shear at the very edge of the plasma, rather than the impurity ion edge rotation shear. However, these experiments do not discriminate against the rotation shear of the main ions, which was not measured.

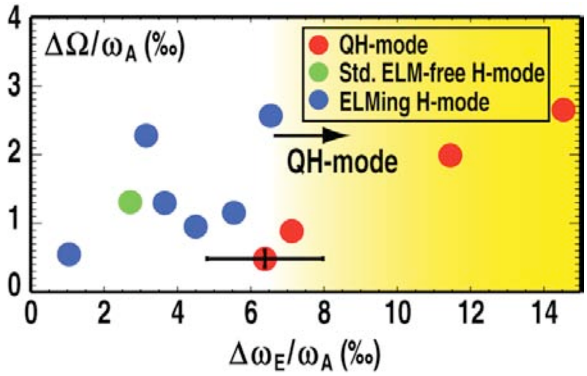

FIG. 7. Edge shear in C impurity ion rotation versus edge shear in ω_E rotation for discharges with different H-mode edge characteristics. Shear is evaluated as the difference between the rotation values across the outer half of the H-mode pedestal, normalized to the local Alfven frequency.

6. Summary

In summary, recent DIII-D experiments have demonstrated new ways in which static non-axisymmetric magnetic fields can improve the tokamak configuration. The counter-I_p torque driven by $n = 3$ NRMFs can be used to replace the torque driven by NBI to maintain the edge rotation shear required for ELM-stable operation in QH-mode even with zero-net NBI torque. Furthermore, the application of the $n = 3$ NRMFs increases plasma resilience to locked modes and allows access to a region of parameter space that, with significant beta and zero-net NBI torque and near-zero core plasma rotation, is otherwise forbidden. Surprisingly, in this regime the energy confinement quality increases with higher β_N. These results provide a challenging new test bed for turbulence suppression models, and rehabilitate the use of non-axisymmetric fields for tearing mode suppression. Above all, these discoveries open a path toward QH-mode utilization as an ELM-stable high confinement regime for the self-heated burning plasma scenario where the torque from neutral beam injection is expected to be little or absent. Future analysis will focus on quantitative benchmarking of the NRMF torque against neoclassical theory, in order to carry out reliable extrapolations to ITER. Further experiments will be aimed at reproducing these results at more ITER-relevant values of the edge safety factor $(q_{95} \sim 3)$, and with values of NBI torque expected in ITER.

Acknowledgment

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