Improving stability and confinement of slowly rotating tokamak plasmas using static nonaxisymmetric magnetic fields

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Abstract. A high-confinement regime without edge localized mode instabilities has been demonstrated for the first time in tokamak plasmas with near-zero rotation and neutral beam torque, by maintaining rotation shear at the edge using static nonaxisymmetric magnetic fields. In this regime, the energy confinement improves with higher plasma pressure. The reduction in energy transport is correlated with a reduction in turbulent fluctuations. Improved resilience to locked modes is also observed.

PACS Nos.: 52.30.Cv, 52.35.Py, 52.55.Fa, 52.55.Tn

The deleterious effects of deviations from the axisymmetry of the magnetic field structure in a tokamak are well known [1]. Reducing these deviations has brought large gains in the fusion performance potential of the tokamak [2]. On the other hand, it is known that the nonaxisymmetric shaping of a toroidal plasma, e.g. in a stellarator, can enable concept improvements such as avoidance of disruptions, no need to drive plasma current, and creation of negative magnetic shear. Recently, a growing emphasis of theoretical and experimental research in magnetic fusion has been directed on the search for an optimization between very small and very large deviations from the axisymmetry of the tokamak. Already, a vast body of studies in that direction has sprung from the observation that nonaxisymmetric fields can, in certain conditions, suppress edge localized modes (ELMs) [3] without the reduction in the neoclassical confinement from orbit losses of helical ripple trapped particles that generally afflicts stellarators.

In this Letter, we report on the first demonstration in a tokamak of the use of nonaxisymmetric fields to achieve the ELM-free regime of quiescent H-mode (QH-mode), in the previously forbidden region of parameter space characterized by significant plasma pressure and near-zero rotation. Without the nonaxisymmetric fields, ELMs appear and locked modes spoil the plasma confinement when the rotation is reduced near zero. Conversely, with applied nonaxisymmetric fields, QH-mode is maintained, resilience to locked modes is improved, and the energy confinement quality increases as the rotation is reduced.

Nonaxisymmetric, mostly nonresonant magnetic fields (NRMFs) of toroidal mode number $n = 3$ are applied to DIII-D plasmas using the I-coil, a set of 12 picture-frame coils distributed toroidally and poloidally inside the vessel [4]. The largest perturbation deliverable by the I-coil is used, which corresponds to a vacuum-calculated flux surface average maximum single $n = 3$ poloidal harmonic $\delta B \sim 12$ Gauss at the plasma surface ($\delta B / B \sim 0.6 \times 10^{-3}$). 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 [$\beta_N = \beta / \left(I_p / aB \right)$ is the normalized β, where $\beta = \langle p \rangle / \left(B^2 / 2\mu_o \right)$ 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 neutral beam injection (NBI) power. The feedback system can also control the injected NBI torque, T_{NBI}, by changing the mix of co- and counter-injected beams. T_{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.

The QH-mode regime is ELM-free 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. In Fig. 1, we show the first evidence that static, $n = 3$ NRMFs can maintain QH mode with lower NBI torque than required without NRMFs. 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 $T_{\mathrm{NBI}} \sim$ -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 $T_{\mathrm{Intr}} \sim$ 2.5 Nm is consistent with the empirical proportionality to the stored energy, "Rice scaling" [8], calculated for DIII-D discharges [9]. 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 $T_{\mathrm{NBI}} \sim 0$. Larger counter-rotation for the same NBI torque is expected based on recent theoretical [10] and experimental [11] 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, $T_{\mathrm{NRMF}} \propto -\left(V_{\phi} - V_{\phi}^{0}\right)$, with V_{ϕ}^{0} the offset rotation. A simple comparison in Fig. 1(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): $T_{\mathrm{NBI}} + T_{\mathrm{NRMF}} + T_{\mathrm{Intr}} - L_{\phi}/\tau_{\phi} = dL_{\phi}/dt$. A more accurate transport analysis technique, described in Ref. [9], yields the profiles of the integrated NRMF and NBI torque densities shown in Fig. 1(f), confirming the simpler analysis. The figure compares integrated torque profiles at times just before the QH-mode phase ends in both discharges. It is shown that the NRMF torque nearly completely compensates for the lower NBI torque in the discharge with the $n = 3$ NRMF applied. 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 results suggest 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 ($\omega_E = E_r / RB_\theta$), not the rotation of the carbon impurity ion. A detailed study of the rotation profiles, beyond the scope of this Letter, will be presented separately.

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 [12], is unchanged during the QH-mode phase with or without the NRMF, as shown in Fig. 1(d). On the other hand, application of the NRMF allows operation at lower NBI torque and plasma rotation than otherwise possible at the same β_N value, and in this previously unexplored region of parameter space the energy confinement quality seems to increase with β_N. This behavior is documented in Fig. 2. 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 $|T_{NBI}|$ ramped down to -1 Nm) shows that the discharge with higher β_N achieves higher energy confinement quality at low $|T_{NBI}|$. The improved confinement correlates with the observation of reduced turbulence levels from Doppler Backscattering measurements [13] 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 $\rho_s = c_s m_i / dB_T$, $c_s = (kT_e/m_i)^{1/2}$). This wavenumber is often associated with trapped electron mode instability. Radial profiles of density fluctuations before and after $|T_{NBI}|$ ramp-down are shown in Fig. 2(f,g). The rotation also decreases substantially at lower $|T_{NBI}|$, as shown in Fig. 2(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 2 shows that 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 [14]. The third discharge shown in Fig. 3 (discharge 141439) further 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 nonaxisymmetric coil set external to the vessel and mainly utilized for $n = 1$ error field correction in these experiments, increased the vacuum $n = 3$ field by ~50% at the plasma boundary in this discharge.)

The application of $n = 3$ NRMFs also increases the stability against locked modes in plasmas with zero-net or small counter-rotation. This is due to two separate 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, set off a metastable neoclassical tearing mode. Figure 1 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 toward zero. A second mechanism is at work in the case shown in Fig. 3. 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 [15]. 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 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 [16]. 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 slow 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.

In summary, recent DIII-D experiments have demonstrated new ways in which static nonaxisymmetric 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-free 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 nonaxisymmetric fields for tearing mode suppression. Above all, these discoveries open a path toward QH-mode utilization as an ELM-free high confinement regime for the self-heated burning plasma scenario where the torque from neutral beam injection is expected to be little or absent.

This work was supported by the US Department of Energy under DE-FC02-04ER54698, DE-FG02-08ER54984, DE-AC02-09CH11466, and DE-FG03-08ER54984. The authors wish to thank E.J. Strait and T.L. Rhodes for helpful discussions.

References

[1] A. Reiman and D. Monticello, *Phys. Fluids B* **3**, 2230 (1991).

[2] A.M. Garofalo *et al.*, *Phys. Rev. Lett.* **89**, 235001 (2002).

[3] T.E. Evans *et al., Nature Physics* **2**, 419 (2006).

[4] G.L. Jackson *et al.*, Proc. of 30th EPS Conf. on Controlled Fusion and Plasma Physics, St. Petersburg, Russia, 2003, Vol. 27A ((European Physical Society) p. P-4.47. http://epsppd.epfl.ch/StPetersburg/PDF/P4_047.PDF

[5] C.M. Greenfield *et al.*, *Phys. Rev. Lett.* **86**, 4544 (2001).

[6] P.B. Snyder *et al.*, *Nucl. Fusion* **47**, 961 (2007).

[7] K.H. Burrell *et al.*, *Phys. Rev. Lett.* **102**, 155003 (2009).

[8] J.E. Rice *et al.*, *Nucl. Fusion* **38**, 75 (1998).

[9] W.M. Solomon *et al.*, *Phys. Plasmas* **17,** 056108 (2010).

[10] A.J. Cole *et al.*, *Phys. Rev. Lett.* **99**, 065001 (2007).

[11] A.M. Garofalo *et al.*, *Phys. Rev. Lett.* **101**, 195005 (2008).

[12] P.N. Yushmanov *et al., Nucl. Fusion* **30**, 1999 (1990).

[13] L. Schmitz *et al.*, *Rev. Sci. Instrum.* **79**, 10F113 (2008).

[14] A.M. Garofalo *et al.*, *Phys. Plasmas* **16,** 056119 (2009).

[15] Q. Yu *et al.*, *Phys. Rev. Lett.* **85**, 2949 (2000).

[16] R.J. La Haye *et al.*, *Phys. Plasmas* **9**, 2051 (2002).

List of Figure Captions

Fig. 1. 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)].

Fig. 2. Effects of NBI torque ramp down in discharges with different values of β_N and of the $n = 3$ NRMF magnitude. 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, and C-coil current; (b) D_α light; (c) NBI torque; (d) confinement quality. Shaded vertical bands labeled (1), (2), and (3) 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), for discharges #138604 and #138605, and over a time range at zero-net NBI torque, (3), for discharge #141439. (f,g) Radial profiles of relative density fluctuation level measured by Doppler backscattering at high and low rotation in discharges #138604 and #138605.

Fig. 3. 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.