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PLASMA ROTATION DRIVEN BY STATIC NONRESONANT MAGNETIC FIELDS

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Plasma Rotation Driven by Static Nonresonant Magnetic Fields

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Predicting the effect of non-resonant magnetic field perturbations on the rotation of a toroidal plasma is a challenging question of plasma science, with important practical implications. Although the braking effect of static magnetic field asymmetries is well known, neoclassical theory [1] implies that in some circumstances they can lead instead to an increase in rotation frequency. This counter-intuitive prediction was recently confirmed in DIII-D experiments [2].

In one of these experiments, $n = 3$ fields that are almost completely non-resonant with respect to the magnetic field lines in the plasma were applied to a set of high β_N, high confinement (H-mode) plasmas with very similar cross-section shape, safety factor q, density and temperature, but different toroidal rotation. The ELMs and the H-mode pedestal are nearly unaffected by the applied $n = 3$ nonresonant magnetic field (NRMF). Temperature, density, and the injected torque reach nearly stationary values before the $n = 3$ field application. The density and injected torque are kept constant across the time of field application. A broad range of shot-to-shot variation in the torque from neutral beam injection, T_{NBI} was achieved by matching plasma conditions with normal and reverse I_p direction, in addition to varying the mix of co- and counter-I_p NBI. The results of this

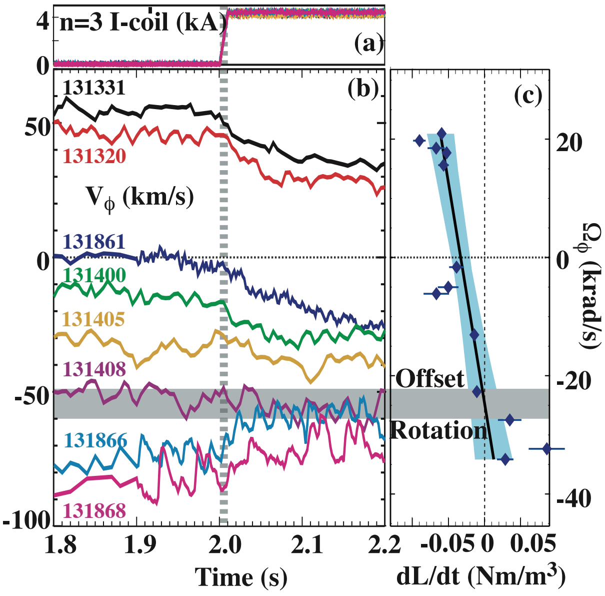

Fig. 1. Time histories of (a) amplitude of $n = 3$ I-coil current and (b) toroidal rotation for plasmas with different values of the (constant) NBI torque. (c) NRMF torque ($= dL/dt$) evaluated at the I-coil current turn-on time for a larger number of discharges. Note that the y-axis in (b) is rotation in km/s at fixed spatial CER view ($\rho \sim 0.8$, major radius $R \sim$ 2.2 m), while in (c) it is rotation in krad/s at fixed ρ ($\rho = 0.8$).

experiment, summarized in Fig. 1, show that the $n = 3$ fields drag the plasma rotation toward a finite "offset" rate in the counter-I_p direction, V_φ^*, so that the torque driven by the nonresonant magnetic field is $T_{NRMF} \propto -(V_\varphi - V_\varphi^*)$. The observed magnitude, direction, and radial profile of the offset rotation are consistent with neoclassical theory predictions. This offset rotation is comparable in magnitude to the ion diamagnetic rotation, but opposite in direction. In a plasma with near zero toroidal rotation, the application of the nonresonant fields leads to an acceleration of the plasma rotation toward V_φ^*.

The offset linear relationship in Fig. 1(c) is only a qualitative representation of the rotation dependence of the NRMF torque. A more quantitative analysis of the NRMF torque requires considering that discharges with different toroidal rotation may fall in different collisionality regimes [3]. In the limit $\nu_{eff} << \omega_E$ (where $\nu_{eff} = \nu_i/\varepsilon$ is the trapped-untrapped ion collision rate, with ν_i the ion collisionality and ε the plasma inverse aspect ratio, and the toroidal component of the $E \times B$ drift, $\omega_E = E_r/RB_\theta$, is approximately the toroidal precessinal drift rate of the banana orbits), the transport enhancement, and therefore the NRMF torque, are predicted to increase with ν_i. This is the so-called ν-regime. At higher collisionality, another regime can be distinguished in the limit $\omega_{ti}\sqrt{\varepsilon} >> \nu_{eff} >> \omega_E$ (where $\omega_{ti} = \sqrt{T_i/m_i}/R_0 q$ is the ion transit frequency). At this higher collisionality, trapped particle effects (and therefore the transport enhancement and NRMF torque) diminish with increasing ν_i. This is the so-called $1/\nu$-regime. The experimental data discussed in this paper falls between the ν and $1/\nu$ asymptotic limits.

Discharges in Fig. 1 with intermediate and high toroidal rotation magnitude ($V_\varphi \geq 30$ km/s) should fall in the ν-regime since $\nu_{eff} \leq \omega_E/10$ across most of the plasma minor radius. However, the scalings of the NRMF torque observed in discharges with intermediate values of co-rotation [4] are more consistent with these plasma discharges being in-between the ν and $1/\nu$ asymptotic limits. The measured NRMF torque shows a strong dependence on both plasma density and temperature. The empirical scalings are not consistent with the predicted values for the ν and $1/\nu$ regimes, when only the I-coil is considered as a source of the NRMF. By assuming that the plasma response gives a contribution to the total perturbed magnetic field inside the plasma comparable to the external field (as suggested by MARS-F [5] modeling results), and by separating the observed beta dependence of the plasma response from the T_i and n_i scalings, the consistency between theoretical and experimental scalings improves from the analysis using only vacuum calculations of the magnetic perturbation. Within the uncertainties in the measurements and in the assumptions, the resulting empirical scalings suggest a torque behavior qualitatively in-between those expected in the asymptotic ν and $1/\nu$ regime limits.

Discharges in Fig. 1 with low toroidal rotation magnitude ($V_\varphi < 30$ km/s) should fall in the $1/\nu$-regime since $\omega_E \to 0$ across most of the plasma minor radius. Indeed, in these cases the T_i and n_i scalings are more consistent with the predictions for the $1/\nu$-regime. Increasing beta at constant density shows a strong increase in the NRMF torque, suggesting a large positive T_i scaling consistent with the $1/\nu$-regime ($T_i^{2.5}$). On the other hand, increasing the density at constant beta shows a reduction of the NRMF torque, suggesting a smaller positive (or negative) density scaling, that also could be consistent with the $1/\nu$-regime (n_i^{-1}).

According to theory, the ν and $1/\nu$ collisionality regimes should also result in a peculiar behavior of the NRMF torque as a function of the plasma rotation at fixed collisionality: a narrow $1/\nu$-regime torque peak, centered about the rotation value for which $\omega_E = 0$. Very recent experiments have begun to show that indeed the measured NRMF torque shows a local peak at rotation values near $V_\varphi \sim -10$ km/s. This small shift in the counter-I_p direction may be consistent with the difference between ω_E and the measured toroidal rotation of carbon impurity ions. In light of these new results, the deviations near $V_\varphi \sim -10$ km/s from the offset-linear behavior of the NRMF torque versus rotation in Fig. 1 can now be understood as indeed part of a $1/\nu$-regime peak.

The magnitude and radial dependence of the offset rotation observed in DIII-D has also been compared to the theoretical scaling for the ν and $1/\nu$ collisionality regimes. The experimentally determined radial profile of the offset rotation, $V_\varphi^{*,\mathrm{exp}}(\rho)$, can be approximated by the actual plasma rotation for discharge 131408 (intermediate counter-rotation in Fig. 1), for which at any minor radius the $n = 3$ braking produces no distinct angular momentum change. The theoretically predicted offset rotation rate is $V_\varphi^{*,\mathrm{NC}} \cong (k_c/Z_i e B_\theta)(dT_i/dr)$, with k_c depending on the collisionality regime [3]. The relationship of $V_\varphi^{*,\mathrm{exp}}(\rho)$ to neoclassical theory can be revealed by the radial profile of $k_c = \left(V_\varphi^{*,\mathrm{exp}}\right) \big/ \left[(1/Z_i e B_\theta)(dT_i/dr)\right]$, as shown in Fig. 5 of Ref. [4]. The figure shows that the plasma is in the ν regime of collisionality to a varying degree for different values of ρ. The values of $k_c(\rho)$ fall between the theoretical limits for the ν and $1/\nu$ regimes. In particular, k_c is closer to the theoretical limit for the ν regime (~0.9) at the ρ values where the plasma is deeper in this regime, consistent with expectations.

The existence of an offset toroidal rotation with direction counter to the plasma current, associated with static, non-axisymmetric, non-resonant fields may offer an explanation to the phenomenon of increasing counter-rotation observed near the plasma edge with increasing toroidal field ripple in the JET tokamak [6]. An important consequence is that the large NRMF torque from high-n fields for edge localized mode (ELM) suppression [7] in a fusion reactor may not represent a problem, but instead supply the dominant rotation torque, since other torque sources are expected to be weak.

In ITER, the NRMF torque from turning on the ELM suppression fields could bring the plasma toroidal rotation close to the counter-I_p offset rotation, even with co-I_p NBI. The expected profiles of the NBI-driven and neoclassical offset rotation are shown in Fig. 11 of Ref. [4]. The offset rotation is about equal in magnitude to the NBI-driven rotation, but it is in the opposite direction.

Toroidal rotation is known to provide several benefits in present tokamak experiments, including flow shear stabilization of turbulence, screening of error fields, and stabilization of resistive wall modes. It is perhaps less known that toroidal rotation in the counter-I_p direction could yield several additional benefits, including: improved $E \times B$ shear suppression of turbulence, due to the pressure gradient and rotation terms of the shearing rate adding to each other in counter-rotation while they oppose each other in co-rotation, and lower power threshold for L- to H-mode transition [8]. In addition, recent DIII-D experiments suggest that the counter-rotation driven solely by a NRMF could satisfy the requirement of minimum velocity shear near the plasma edge for access to QH-mode, a quiescent, i.e. ELM-free, type of H-mode [9].

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