Reduced Critical Rotation for Resistive-Wall Mode Stabilization in a Near-Axisymmetric Configuration

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Recent DIII-D experiments with reduced neutral beam torque and minimum nonaxisymmetric perturbations of the magnetic field show a significant reduction of the toroidal plasma rotation required for the stabilization of the resistive-wall mode (RWM) below the threshold values observed in experiments that apply nonaxisymmetric magnetic fields to slow the plasma rotation. A toroidal rotation frequency of less than 10 krad/s at the $q = 2$ surface (measured with charge exchange recombination spectroscopy using C VI) corresponding to 0.3% of the inverse of the toroidal Alfvén time is sufficient to sustain the plasma pressure above the ideal MHD no-wall stability limit. The low-rotation threshold is found to be consistent with predictions by a kinetic model of RWM damping.

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The stabilization of long-wavelength kink instabilities in the presence of a resistive wall by plasma flow is an important problem of magnetohydrodynamic (MHD) physics. It also has practical importance, since several magnetic confinement schemes for high-pressure plasmas rely on such wall stabilization, including advanced tokamak scenarios for future fusion plasmas [1]. Without any conducting wall, ideal MHD theory predicts that the plasma pressure is limited by a long-wavelength kink mode. Finite conductivity of a nearby structure, such as a vessel wall, can convert this fast growing kink mode into a slowly growing resistive-wall mode (RWM), albeit with no improvement over the no-wall stability limit [2]. The stability can, however, be improved by rotating the plasma with respect to the wall [3–5]. In the DIII-D tokamak, rapid toroidal plasma rotation has been successful in stabilizing the RWM and sustaining the plasma pressure up to the significantly higher ideal MHD limit assuming an ideally conducting wall [6]. While these experiments predominantly use tangential neutral beam injection (NBI) for heating, which couples heating power and toroidal torque, a fusion reactor with its dominant alpha particle heating will have to rely on less externally applied torque. In order to measure the rotation threshold for RWM stabilization and project it to a fusion reactor, experiments with unidirectional NBI heating have used "magnetic braking" by the intrinsic error field or externally applied nonaxisymmetric magnetic fields with a $n = 1$ component [4,7]. Parametric scans in DIII-D [7], as well as the comparison between similar plasmas in DIII-D and JET [8], indicated the importance of the rotation at the $q = 2$ surface for RWM stabilization. Depending on the scenario the critical rotation frequency Ω_{crit} at the $q = 2$ surface in DIII-D ranged from 0.7% to 2.5% of the inverse of the local Alfvén time $\tau_A = R_0(\mu_0\rho)^{1/2}/B_0$, where R_0 is the major radius, B_0 the toroidal magnetic field on axis, and ρ the local mass density [7–9].

In this Letter we report a surprisingly low-rotation threshold for RWM stabilization in DIII-D experiments with a near-axisymmetric configuration, compared to the thresholds observed with magnetic braking. Here the threshold is evaluated at $q = 2$, which is the lowest order resonant surface of the $n = 1$ mode. The new results have been made possible by the redirection of one of the four two-source NBI beam lines. In the new configuration DIII-D has the capability to control the rotation independent of the heating power and to apply up to 10 MW of NBI power P_{NBI} without injecting a net torque T_{NBI}, removing the necessity for a nonaxisymmetric magnetic field to slow the rotation.

Without the stabilizing effect of plasma rotation, the RWM is expected to limit the plasma β to the ideal MHD no-wall stability limit $\beta_{no\text{-}wall}$, which is typically set by the $n = 1$ mode ($\beta = 2\mu_0\langle p\rangle/B_0^2$ is the ratio of plasma pressure p and magnetic field pressure and $\beta_N = \beta(\%) \times [a(m)B(T)/I(\mathrm{MA})]$ is the "normalized β" with a being the minor radius of the plasma and I the plasma current). This is confirmed in discharge 126 389, Fig. 1, where β_N is ramped up with nearly balanced NBI torque of $T_{NBI} < 0.8$ Nm, which is about 10 times lower than T_{NBI} with unidirection NBI heating at the same power. At $\beta_N \approx 2.1$ a slowly growing and nonrotating $n = 1$ mode leads to a beta collapse. Ideal MHD stability calculations for multiple discharges and times using the DCON code [10] predict that the no-wall beta limit in this type of discharge, which is a "weakly" shaped lower single-null discharge with a monotonic or slightly reversed central safety factor profile and $1 < q_{min} < 2$, Fig. 2, is approximately

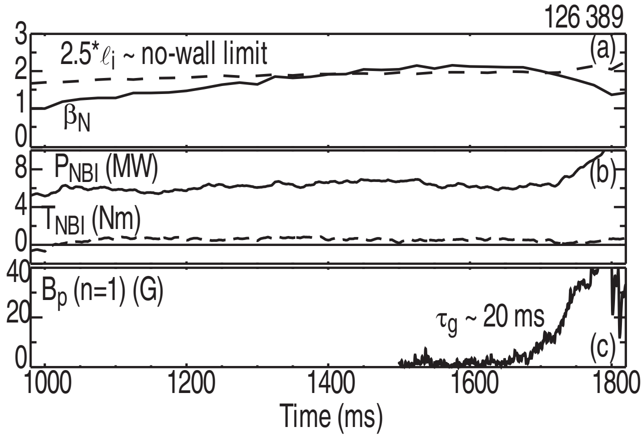

FIG. 1. In discharge 126 389 β_N is ramped up (a) by increasing the NBI heating power $P_{\rm NBI}$ while keeping the NBI torque $T_{\rm NBI}$ low (b). Measurements of the poloidal magnetic field B_p show that the high β phase is terminated by a nonrotating $n = 1$ mode with a characteristic growth time $\tau_g = 20$ ms (c). The increase in $P_{\rm NBI}$ after $t = 1720$ ms is due to the feedback system unsuccessfully trying to increase β_N as the mode grows.

$\beta_{N,\text{no-wall}} \approx (2.5 \pm 0.1)\ell_i$, where ℓ_i is the plasma internal inductance. Thus, the mode onset in discharge 126 389 occurs when β_N exceeds the predicted no-wall limit by approximately 5%, Fig. 1(a). The observed growth time of $\tau_g \approx 20$ ms, Fig. 1(c), corresponds to about seven characteristic resistive decay times τ_w of a typical RWM eddy current pattern in the DIII-D vessel and is consistent with a RWM just above the no-wall stability limit.

The rotation threshold for the stabilization of the RWM is measured by establishing a rapidly rotating discharge with dominant NBI in the direction of the plasma current (''co''-injection) before replacing co-beams with NBI in

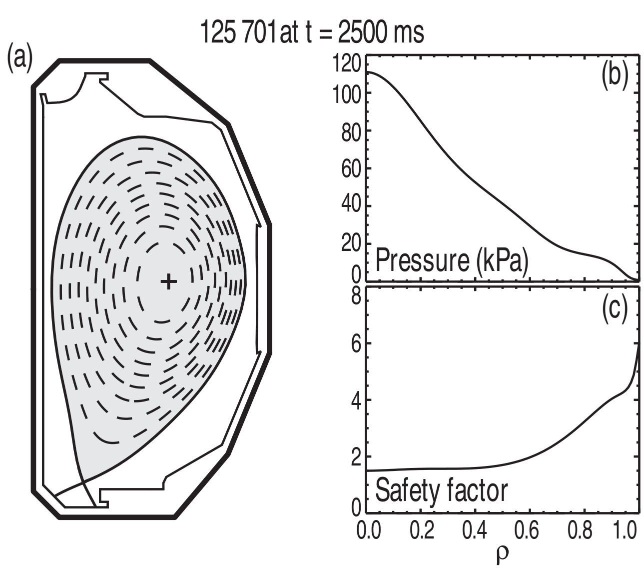

FIG. 2. Plasma cross-section and DIII-D wall geometry (a), pressure (b), and safety factor (c) profiles of a typical discharge of the low-rotation study.

the opposite direction (''counter''-injection), thereby reducing $T_{\rm NBI}$, Figs. 3(a)–3(e). In discharge 125 709 NBI feedback controls β_N at a value of 2.3, which in this discharge is approximately 15% above $\beta_{N,\text{no-wall}}$, Fig. 3(a). The external nonaxisymmetric coils (''C coils'') are used to minimize the $n = 1$ component of the intrinsic error field throughout the entire discharge, Fig. 3(b). Starting at $t = 2300$ ms $T_{\rm NBI}$ is gradually reduced, Fig. 3(b) and the plasma rotation decreases, Fig. 3(c). Surprisingly, the rotation at the $q = 2$ surface decreases to a value as low as 10 krad/s before the RWM becomes unstable at $t = 3030$ ms, Fig. 3(d). At the mode onset, the rotation across a large part of the profile is very small, Fig. 3(i). The profile shape is partially caused by the different absorption profiles of co- and counterbeams. The rotation at the $q = 2$ surface is less than 0.3% of the inverse Alfvén time, Fig. 3(j), which is significantly lower than the values of 0.7% to 2.5% that were previously observed in DIII-D with magnetic braking, albeit in slightly different discharge scenarios [7–9]. Experiments with NBI torque rampdowns at various values of β above $\beta_{\text{no-wall}}$ reveal no appreciable β dependence of the rotation threshold. The observed rotation threshold is remarkably similar to the values obtained in recent JT60-U experiments, which also used low NBI torque [11].

The plasma rotation in these DIII-D experiments as in the previous experiments is measured with a charge exchange recombination (CER) diagnostic using C VI, which yields the toroidal and poloidal rotation velocity of carbon impurity ions across the outer half of the plasma cross section. It is usually assumed that impurity rotation is an estimate of the main ion (deuterium) rotation and that the corresponding rotation frequency $\Omega_{\rm rot}$ is a flux surface quantity. The difference between carbon and deuterium rotation is predicted by neoclassical theory, although it has been shown that the theory is not complete [12].

In order to compare the rotation thresholds, magnetic braking is applied in a plasma similar to discharge 125 709, Figs. 3(e)–3(h). Using co-NBI only, discharge 126 571 exceeds the no-wall limit by about 25%. Starting at $t = 2200$ ms, the error field correction currents in the C coil are ramped-down, effectively increasing the $n = 1$ component of the magnetic field, Fig. 3(f), and causing a slow decrease of the plasma rotation, Fig. 3(g). The $n = 1$ field is resonant with the weakly damped $n = 1$ RWM and leads to resonant field amplification (RFA) [13], which shows up as an increasing plasma response, Fig. 3(h). The transition from the slowly increasing plasma response to a faster growth has been interpreted as the transition from RFA to an unstable RWM and has, thereby, yielded a measurement of the critical rotation [9]. In discharge 126 571 this transition occurs at approximately $t = 2250$ ms at a plasma rotation, which is significantly larger than the rotation threshold obtained without applying a nonaxisymmetric field, Fig. 3(i). The rotation threshold at the $q = 2$ surface corresponds to 1.9% of the inverse Alfvén time,

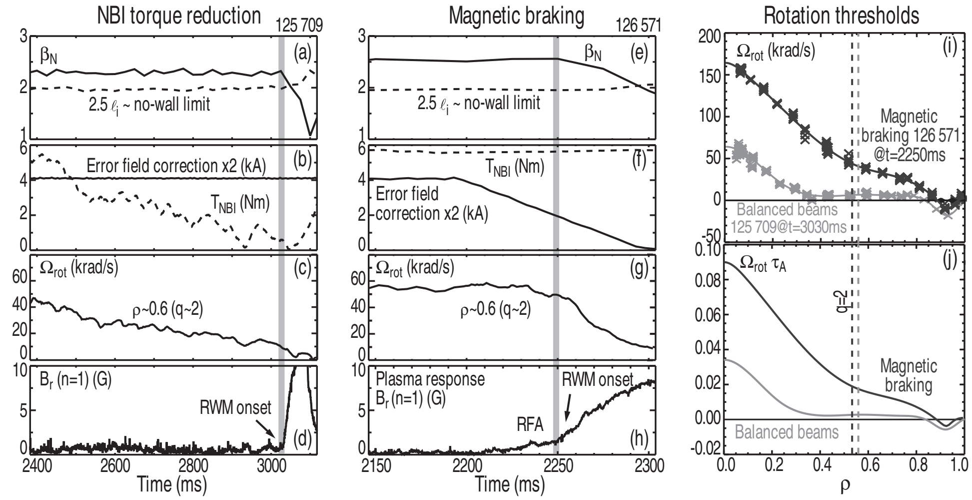

FIG. 3. Rotation threshold determined by reducing the NBI torque in discharge 125 709 (a)–(d) and by magnetic braking in discharge 126 571(e)–(h). Shown are β_N (a),(e), NBI torque T_{NBI} and error field correction currents (b),(f), plasma rotation (from CER diagnostic using C VI) at the $q = 2$ surface (c),(g) and the $n = 1$ component of the plasma generated radial magnetic field B_r measured at the vessel wall (d),(h). The two methods yield different (normalized) critical rotation profiles (i),(j).

Fig. 3(j), which is within the range observed in previous magnetic braking experiments.

In discharge 126 496 it is demonstrated that plasma rotation just above the low threshold observed in the near-axisymmetric configuration is sufficient to sustain β above $\beta_{\text{no-wall}}$, Fig. 4. Feedback control of P_{NBI} maintains $\beta_N = 2.4$, which is 20% above the no-wall limit, Fig. 4(a). A ramp-down of T_{NBI} is halted at $t = 2800$ ms at a low value, Fig. 4(b). At $t \approx 3100$ ms the discharge reaches a stationary low rotation with the value at the $q = 2$ surface corresponding to approximately 0.3% of the inverse Alfvén time. The stable operation is sustained for about 800 ms, corresponding to approximately 250 characteristic wall times, Fig. 4(c), which shows that the stabilization of the RWM with the reduced rotation is not just a transient phenomenon.

There are at least two possible reasons for the difference between the present observations of a low-rotation threshold for RWM stabilization obtained with low NBI torque in a near-axisymmetric configuration and previous measurements obtained with a large NBI torque and magnetic braking. In these discharges, the applied magnetic perturbation had always a strong $n = 1$ component, which is resonant with the RWM as well as with several singular flux surfaces. A hypothesis that could explain the observed behavior involves the resonant response of the plasma to external magnetic perturbations [14,15]. At high rotation, induced currents at singular resonant surfaces shield the externally applied magnetic field and lead to a decrease of the plasma rotation. At some lower rotation the shielding becomes insufficient, torque balance equilibrium is lost, and a bifurcation with a rapid rotation collapse occurs. The RWM would only become unstable during the collapse of the plasma rotation, which would be later than presently thought, leading to an overestimation of the critical rotation for RWM stabilization. Alternatively, the different rotation thresholds, in particular, the value observed at the $q = 2$ surface, could be explained by the different rotation profile shapes obtained with reduced NBI torque and magnetic braking. While magnetic braking decreases the magnitude of the rotation across the entire profile, the addition of counter NBI can lead to significant counter-rotation near the plasma edge. An increased importance of the rotation at these higher q *resonant* surfaces in the

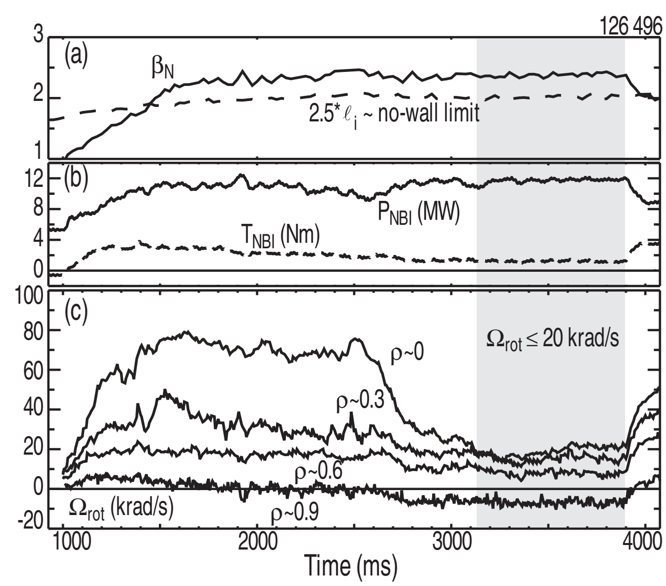

FIG. 4. In discharge 126 496 β_N is sustained above the no-wall limit (a) with nearly balanced NBI heating (b) for about 800 ms with rotation below 20 krad/s across the entire profile (c). At $t = 3900$ ms the maximum pulse length of one of the counter-NBI sources limits the duration of the low-rotation, high β phase.

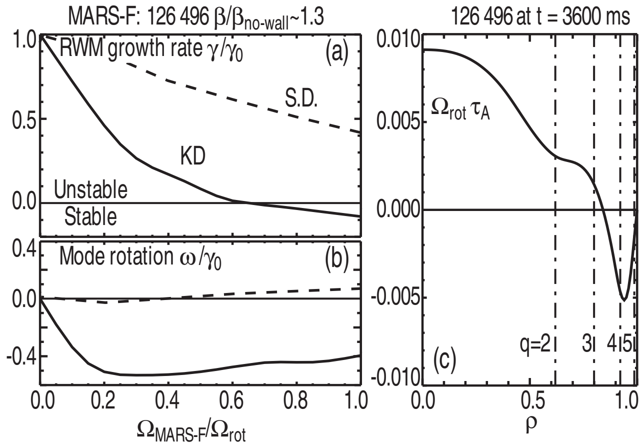

FIG. 5. Kinetic damping (KD) and sound wave damping using $\kappa_{||} = 1$ (SD) predict the dependence of the RWM growth rate γ (a) and mode rotation frequency ω (b) on a scale factor of the plasma rotation measured in discharge 126 496 at $t = 3600$ ms, $\Omega_{\text{MARS-F}}/\Omega_{\text{rot}}$ (c). Growth rate and mode rotation are normalized on the growth rate without rotation γ_0.

stabilization mechanism over the $q = 2$ surface, could reconcile the apparently different rotation thresholds.

The low-rotation threshold observed with low NBI torque also challenges stabilization theories. Promising stabilization models include the sound wave damping [16] and the kinetic damping [17] models, both implemented in the MARS-F code [18]. While the sound wave damping model contains a free parameter $\kappa_{||}$, which can be adjusted to match experimental results the kinetic model yields an absolute prediction. So far, the kinetic model, which takes into account the resonances of passing particles with the ion transit frequency and of trapped particles with the bounce frequency, has underestimated the critical rotation measurements obtained with magnetic braking in DIII-D by 20% to 70% [7–9]. Calculations using scaled rotation profiles of the low NBI torque discharge in Fig. 4 yields that, with kinetic damping about 70% of the experimental rotation should be sufficient for stabilization, whereas with soundwave damping and a moderate value of $\kappa_{||} = 1$, the experimental rotation is not sufficient, Fig. 5(a). Interestingly, the kinetic damping model predicts a mode rotation frequency at marginal stability in the counter direction, Fig. 5(b), which corresponds to the direction of the rotation at the $q = 4$ surface rather than at the $q = 2$ surface, Fig. 5(c). A quantitative analysis, however, has to take into account the difference between the measured impurity rotation and the main ion rotation as well as the ion diamagnetic rotation, which are both in the order of the measured rotation. The stabilizing effect of the resonance with the drift frequency of trapped particles [19] needs to be evaluated, too. These first calculations nevertheless suggest that both an overestimation of the critical rotation caused by resonant magnetic braking and an increased role of higher integer q surfaces in the stabilization process contribute to the difference in the rotation thresholds found with magnetic braking and with reduced NBI torque. The kinetic damping model appears as a promising candidate to explain the low-rotation threshold for RWM stabilization.

The low-rotation threshold observed in plasmas with a low NBI torque is encouraging for the confinement of high-pressure self-heated fusion plasmas with little externally applied torque. However, the observation of a higher rotation threshold in the presence of nonaxisymmetric fields does imply an upper limit on tolerable magnetic field errors when β exceeds $\beta_{\text{no-wall}}$. The new observations suggest that critical rotations obtained with magnetic braking overestimate the linear rotation threshold for RWM stabilization and new modeling indicates the importance of the rotation near the plasma edge for the stabilization mechanism, which opens a door to reconcile the previous and the new experimental observations with the kinetic damping model.

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