# Influence of plasma flow shear on tearing in DIII-D hybrids

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Resistive tearing modes are the principal limit to high beta tokamak performance in plasmas which are otherwise ideal kink stable. A variety of tokamaks in an assortment of regimes with a medley of tearing modes have found that removing plasma rotation has a destabilizing effect [1-5]. The theoretical work is generally at low beta and is concerned with the classical tearing mode, $\Delta' < 0$ stable, $\Delta' > 0$ unstable. The theoretical effects have been sorted out as to regime in [6]. The empirical model in [5] suggests that flow shear makes $\Delta'$ more negative (more stable), both reducing the amplitude of neoclassical tearing modes (NTMs are sustained by the helically perturbed bootstrap current) and making the destabilization harder, i.e. requiring a higher beta.

The hybrid scenario is one in which the plasma is operated at about the no wall $n = 1$ kink beta limit (but of course with a resistive wall) with periodic peeling/ballooning edge localized modes (ELMs) and without sawteeth [7]. While the beta limit is determined by the onset of an m/n = 2/1 NTM, the existence of a m/n = 3/2 or 4/3 NTM is needed to sustain the relatively flat core $q$-profile against resistive diffusion and keep the safety factor on axis $q(0) > 1$ so as to avoid sawteeth [8]. In this paper, we extend the previous study [5] of NTM amplitude and onset for 3/2 or 2/1 modes in various devices and regimes to the specific regime of the DIII-D hybrid scenario with m/n = 4/3 modes [9,10]. There is clearly yet again an advantage for improved tearing stability by having strong applied torque and large driven rotation. Future tokamaks with relatively large inertia should endeavor to include as much torque as possible in the design.

**Experimental Setup**

Operation of the hybrid discharge is discussed in Refs. [7-10] with note of m/n = 4/3 hybrids in Refs. [9-10]. All discharges have plasma current $I_p$ = 1.2MA, toroidal field on axis $B_T$ = 1.8T, safety factor at the 95% flux surface $q_{95}$ = 4.2, minor radius $a$ = 0.60m, major radius $R_0$=1.75m elongation $\kappa$ = 1.73, upper triangularity $\delta_u = 0.65$ and lower triangularity $\delta_\ell = 0.32$. Equilibrium reconstruction constrained by the motional Stark effect (MSE) polarimetry is performed by the code EFIT. The line averaged density $\bar{n} \approx 3.9\times10^{19} m^{-3}$ is kept constant under feedback with “puff and pump”. The normalized beta $\beta_N = \beta(\%)/(I_P/aB_T) \approx 2.7$ with $\beta$ the ratio of the volume averaged plasma pressure to the magnetic field pressure; this is kept constant by feedback of the neutral beam injected (NBI) power and in some discharges is raised to test the m/n = 2/1 mode stability limit or lowered to test the limit with reduced rotation. All discharges selected for analysis have m/n = 4/3 modes, are ELMing and have periodic brief beam driven m/n = 1/1 fishbone instabilities which tend to chirp down in frequency. Rotation is varied by feedback control of the applied NBI torque by mixing in counter beams to previously all-co beams; the neutral beam injection feedback acts to simultaneously keep both beta and torque as programmed. Toroidal rotation of CVI impurity ions is measured by the multi-chord charge exchange recombination (CER) diagnostic.

**Effect of changing the applied torque on the amplitude of m/n = 4/3 tearing modes**

The amplitude of m/n = 4/3 modes gets larger as applied torque is reduced and the plasma flow (rotation) and flow shear are decreased. The plasma $\beta_N$ is maintained constant by increasing the NBI power as energy confinement decreases with lower rotation. The tangentially viewing CER gives a good measure of the $n$ = 3 island rotation. The island rotation tends to be a little faster in the ion diamagnetic drift direction than the CVI toroidal rotation [11]. The m/n = 4/3 Mirnov amplitude $|\tilde{B}_\theta|$ before end of flattop (if no 2/1 mode) or just before m/n = 2/1 onset versus flow shear are shown in Fig. 1. A third order polynomial fit recovers the apparent irreducible limit below which flow shear has no effect. Flow shear of about -290 krad/s/m is needed to decrease $|\tilde{B}_\theta|$ by a factor of 4; the irreducible level is about a factor of 9 and occurs at -450 krad/s/m.

A technique for inferring (measuring) the effective $\Delta'$ with islands which are not (or slowly) varying in width with time was presented in Refs. [4-5]. A working relation for NTMs sustained by a helically perturbed bootstrap current is the modified Rutherford equation (MRE)

$$\frac{\tau_R}{r^2}\frac{dw}{dt} \approx \Delta' + \varepsilon^{1/2}\frac{L_q}{L_{pe}}\beta_{\theta e}\left(\frac{1}{w} - \frac{w_{marg}^2}{3w^3}\right) \approx 0 \quad (1)$$

where $w$ is the full island width, $\varepsilon = r/R_0$ and $L_q = q/(dq/dr)$ are the local inverse aspect ratio and radial magnetic shear length, respectively, $\beta_{\theta e} = 2\mu_0 k_B n_e T_e / B_\theta^2$ is the local *electron* beta poloidal and $L_{pe} = -p_e/(dp_e/dr)$ is the local gradient radial scale length in the electron pressure. The quantity $w_{marg}$ is here simplified and incorporates all the small island stabilizing effects and is typically of order twice the ion banana width; $w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}$ where $\rho_{\theta i} \equiv \left(2m_i T_i / eB_\theta^2\right)^{1/2}$. Equation (1) assumes that the equilibrium bootstrap current $j_{boot}$ is approximately dominated by electrons and is about $\varepsilon^{1/2} B_\theta \beta_{\theta e}/2\mu_0 L_{pe}$. $\Delta'$ is evaluated experimentally from Eq. (1) using EFIT with MSE to get the MHD equilibrium, Thomson scattering to get profiles of $p_e$, and CER to get $T_i$ for $\rho_{\theta i}$. Island widths come from analysis of Mirnov amplitude using the EFIT and benchmarked by the island width from electron cyclotron emission ECE diagnostic of a large island case [4-5].

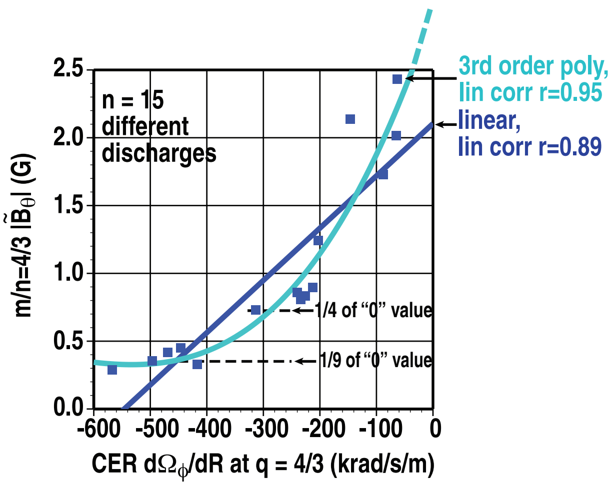


Fig. 1. m/n = 4/3 amplitude $|\tilde{B}_\theta|$ versus flow shear at the outer q = 4/3 surface. Both linear and 3rd order polynomial fits are shown. The flow shear to reduce $|\tilde{B}_\theta|$ by 1/4 and 1/9 are noted.

The inferred $\Delta'$ for 4/3 islands is more negative (stable) with more negative flow shear as shown in Fig. 2. $\Delta'$r is plotted versus the normalized flow shear (NFS) in which flow shear is put into context by comparing to the inverse of the parallel magnetic shear length $\left(L_s = q L_q/\varepsilon\right)$ divided by the Alfvén time $\left(\tau_A = R_o\sqrt{\mu_o n_e m_i / B_T^2}\right)$ [5,10]. For $w_{marg} \equiv 0$, $\Delta' r$ decreases linearly with NFS with a linear correlation of 0.907. Note that the 3 highest $|\tilde{B}_\theta|$ values in Figure 1 cannot be analyzed due to missing Thomson data from a blocked shutter. Note also that the irreducible minimum in $|\tilde{B}_\theta|$ of Figure 1 with large negative flow shear is not resolvable in Figure 2 although one must point out that multiple gradients now appear both in y and x axes and add scatter. Including $w_{marg} \equiv 2\varepsilon^{1/2}\rho_{\theta i}$, the decrease in $\Delta' r$ with NFS is still linear and with a very slightly higher linear correlation of 0.911 but not as strong an effect. Here as flow shear is increased, decreasing $\Delta'$ and reducing the island size, the small island stabilizing effects become larger, further reducing the island size.

**Destabilization of m/n = 2/1 tearing modes with reduced torque or higher beta**

Reduced plasma rotation experimentally destabilizes a previously stable m/n = 2/1 tearing mode. As the plasma rotation is decreased, the negative flow shear at q = 2 decreases. The initial m/n = 2/1 Mirnov frequency is well correlated with the CER profile fit to the EFIT q=2 location, and the island rotates consistently faster in the ion diamagnetic drift direction than the CER CVI toroidal rotation.

The stability of m/n = 2/1 tearing for $\beta_N$ versus flow shear is shown in Fig. 3. Stable operation is lost with only about a 5% rise in beta for discharges with strong flow shear. The 2/1 onset beta decreases by about 15% when all flow shear is removed. The transient nature of the growing mode makes the backing out of $\Delta'$ from Eq. (1) problematic due to the need to evaluate the non-zero $(\tau_R/r)dw/dt$. Here $\tau_A^{-1}/L_s \approx (0.337\mu sec)^{-1}/2.19m \approx 1355$krad/s/m for #127780 at t = 3425 ms with all co-NBI for example. Thus the NFS for a factor of 1.15 in $\beta_N$ from the fit of Fig. 3 is $-(d\Omega_\phi/dR)L_s\tau_A \approx 0.25$. This implies a more negative $\Delta'$ by 1.15 times in going from NFS = 0 to 0.25 which would raise the stable beta by 15% if everything else is equal.

**m/n=2/1 mode locking to the resistive wall**

The fields of rotating islands induce eddy currents in the resistive vacuum vessel wall. The fields of the eddy currents in turn, exert drag on the islands. If large enough, a critical point is reached in which the slowed island rotation cannot be sustained and the island locks to the wall [12,13]. The 2/1 onset discharges here with a range of applied torque

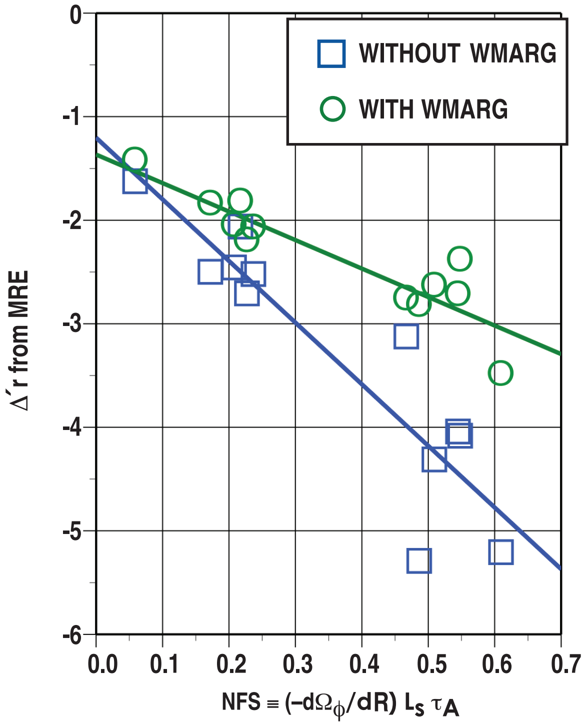


Figure 2. Inferred $\Delta' r$ from the MRE balance versus normalized flow shear from m/n = 4/3 islands (with and without small island stabilization effects characterized by $w_{marg}$ of twice the ion banana width.)

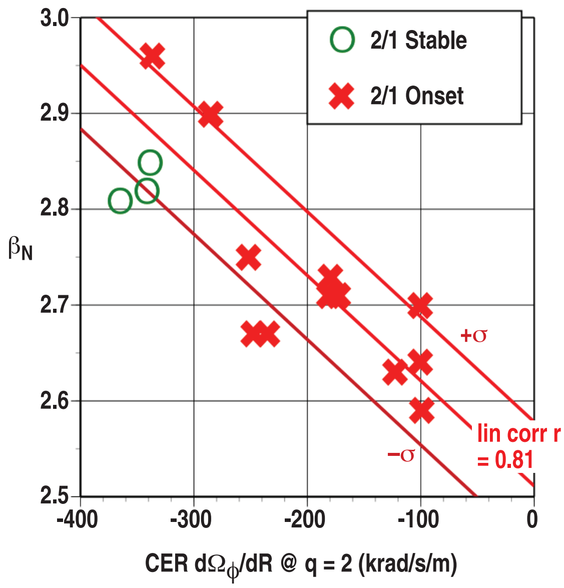


Fig. 3. $\beta_N$ for stability of m/n = 2/1 tearing versus flow shear from CER at q = 2 from EFIT with MSE. The best linear fit of the mode onset vs. flow shear is shown with $\pm\sigma$ standard deviation.

now allow further testing of the physics of the critical condition for mode locking. Absent an island, the balance of applied torque and plasma viscosity produces a rotation $\Omega_{\phi o}$. Equilibria with increasing island width exist up to the point where $\Omega_{\phi}/\Omega_{\phi o} = 1/2$. Larger island widths have no torque balance and locking results. This condition is $(w/a)^4 \geq mC_w \tau_{A\theta}^2 \tau_w \Omega_{\phi 0}^2 / 4\tau_v$ with $\tau_w$ the resistive wall time, $\tau_v$ the viscous time (estimated as $\tau_E$ ) and $\tau_{A\theta}^2 = R_o^2(\mu_o n_e m_i)/2B_\theta^2$. The simple scaling is then locking at $\Omega_{\phi}/\Omega_{\phi o} = 1/2$ and $|\tilde{B}_\theta|^2$ at locking proportional to $\Omega_{\phi o}^2$. The experimental curves of $\Omega_\phi$(t) with a growing mode have a "slow" decrease followed by a "fast" decrease with time. At the intersection, the "knee", one determines the "point of no return" for locking; this is plotted versus the initial onset rotation (after seeding but when the mode is still small) in Figure 4(a). The best fit has a ratio of 0.47. The square of the n = 1 Mirnov amplitude at the knee is plotted versus the initial rotation in Fig. 4(b). The larger the applied torque, the larger the initial mode rotation and the larger $|\tilde{B}_\theta|^2$ has to be for torque balance to be lost. However, $|\tilde{B}_\theta|^2 \propto \Omega_{\phi o}$ and not $\propto$ to $\Omega_{\phi o}^2$ as in the simple theory. As for the single all co-NBI case of Ref. [13], some extra physics is needed to model the effect of the growing island and/or the decreasing flow shear at the island on the local viscosity and thus viscous time $\tau_v$. With $(w/a)^4 \propto |\tilde{B}_\theta|^2 \propto \tau_{A\theta}^2 \tau_w \Omega_{\phi o}^2 / \tau_v$, the observed scaling $|\tilde{B}_\theta|^2 \propto \Omega_{\phi o}$ is recovered for fixed $\tau_{A\theta}$ and $\tau_w$, with $\tau_v \approx r^2/v_\perp$ and local $v_\perp \propto -1/(d\Omega_\phi/dr)$.

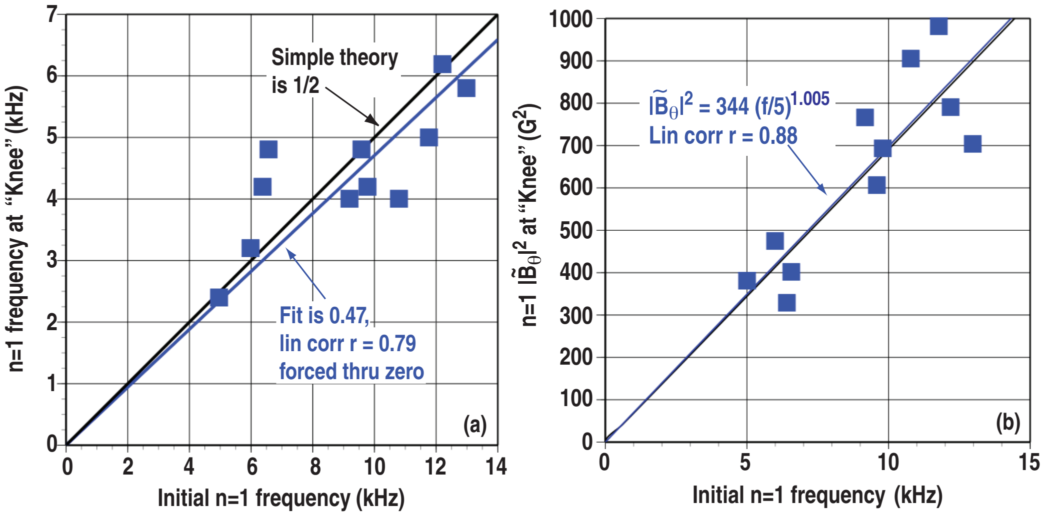


Figure 4 (a). n= 1 Mirnov rotation at the critical point for locking ("the knee") versus initial rotation at onset. (b). Square of the n = 1 Mirnov amplitude at the critical point versus the initial n =1 Mirnov rotation.

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