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METASTABLE BETA LIMIT IN DIII–D*

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The long-pulse, slowly evolving single-null divertor (SND) discharges in DIII–D with H–mode, ELMs, and sawteeth are found to be limited significantly below (factor of 2) the predicted ideal limit $\beta_N = 4\,\ell_i$ by the onset of tearing modes. The tearing modes are *metastable* in that they are explained by the neoclassical bootstrap current (high β_θ) destabilization of a seed island which occurs even if $\Delta' < 0$, i.e., otherwise stable. For sufficiently high β_θ, there is a region of the modified Rutherford equation such that $dw/dt > 0$ for w larger than a threshold value; the plasma is *metastable*, awaiting the critical perturbation which is then amplified to the much larger saturated island.

Experimental results from a large number of tokamaks indicate that the high beta operational envelope of the tokamak is well defined by ideal magnetohydrodynamic (MHD) theory [1,2] and is given by $\beta(\%) \lesssim 4\ell_i I/aB$ MA/m/T for a large range of conditions. The highest beta values achieved have historically been obtained in fairly short pulse discharges, often <1–2 sawteeth periods and <1–2 energy replacement times. The maximum operational beta in single-null divertor (SND), long-pulse discharges in DIII–D with a cross-sectional shape similar to the proposed ITER tokamak (Fig. 1) is found to be limited significantly below the threshold for ideal instabilities by the onset of resistive MHD instabilities. [A hard disruptive beta limit is usually considered to be due to ideal MHD instabilities, either the n=1 kink or the n=∞ ballooning mode where n is the toroidal mode number.] The temporal evolution of a typical discharge is shown in Fig. 2; the beam power is increased gradually. There is a "soft" beta limit due to the onset of an m/n = 3/2 rotating tearing mode which saturates at an amplitude that decreases energy confinement by $\Delta\tau_E/\tau_E \approx -20\%$ [Fig. 2(b,c)] and a "hard" beta limit at slightly higher beta due to the onset of an m/n = 2/1 rotating tearing mode which grows to an amplitude that destroys the confinement and induces a disruption [Fig. 2(b,d)]. (These plasmas are neutral beam heated ELMing H–mode with sawteeth; the safety factor q_{95} is just above 3.)

An explanation of the observed experimental results is consistent with the neoclassical bootstrap current destabilization of a seed island for otherwise stable plasmas, i.e. $\Delta' < 0$ where Δ' is a measure of the free energy available from the poloidal field. For this study, Δ' is estimated from an analytical approximaton using the MHD reconstruction EFIT [3,4]. The effect of the bootstrap current is increasingly more destabilizing with increased beta poloidal β_θ as is seen from the the modified Rutherford equation for island of width w [5]

$$\left(\frac{\mu_0}{1.22\,\eta_{nc}}\right)\frac{dw}{dt} = \Delta' + a_1 \varepsilon^{1/2}\beta_\theta\left(\frac{L_q}{L_p}\right)\left[\frac{w}{\left(w^2+w_d^2\right)}\right] - a_2 g\left(\varepsilon,\nu_i\right)\frac{\left(L_q/L_p\right)^2}{w^3}\rho_{\theta i}^2\beta_\theta$$

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where the second term on the RHS is usually ($L_q/L_p > 0$) destabilizing. ($L_q \equiv q/dq/dr$ and $L_p \equiv -p/dp/dr$ with a_1 and a_2 and constants of order one.) Other MHD events such as sawteeth or ELMs usually trigger the onset of the resistive modes, supporting the idea that they are neoclassically destabilized by a seed perturbation. The neoclassical destabilization of tearing modes requires the proper conditions, i.e., high beta and low collisionality, and a seed island. The collisionality can enter (for $\Delta' < 0$) in either of two ways. In the "$\chi_\perp/\chi_{||}$" model [6], the pressure is not equilibrated on the perturbed flux surface when perpendicular transport $\chi_\perp$ across a seed island dominates over that along the island $\chi_{||}$, so that the critical island width w_d is an increasing function of collisionality. In the "$\omega*$" model [7], the toroidally enhanced ion polarization drift response of the plasma to the seed island due to inertial effects can add a stabilizing term to the modified Rutherford equation (the third term on the RHS) which dominates at small w. (Whether it is stabilizing depends on the mode frequency in the $E_r = 0$ frame, here assumed stabilizing.) It has a collisional factor $g(\varepsilon,\nu_i) = \varepsilon^{3/2}$ for $\nu_i/\varepsilon\omega_{*e} \ll 1$ and $g(\varepsilon,\nu_i) = 1$ for $\nu_i/\varepsilon\omega_{*e} \gg 1$ that can increase the critical island size a factor of 2–3. [Bootstrap current also requires $\nu_* \equiv (\nu_i/\varepsilon/\omega_{bi})$ be well below one where $\omega_{bi} = \varepsilon^{1/2}\, v_i/qR$.]

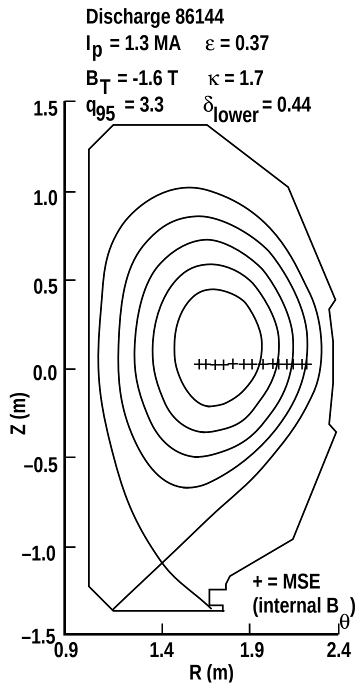

Fig. 1. Equilibrium cross section in DIII–D similar to that proposed for ITER. The 16 radial positions of the MSE diagnostic of poloidal field profile are also shown.

The ITER-like discharges in DIII–D have both sawteeth and ELM perturbations with the sawteeth period 10 to 20 times that of the ELMs. Examination of the databases of the onset of m/n=3/2 and 2/1 modes shows: (1) in 16 of 17 cases of the onset of the 3/2 mode, the mode clearly starts on a sawtooth crash with the remaining case on what may be an impurity burst, (2) the onset of the 2/1 mode is uncorrelated with a sawtooth crash but instead appears coincident with an ELM in 18 of 18 cases. For discharge #86144 of Fig. 2, as β_θ slowly increases and collisionality [here $\nu_* \equiv (\nu_i/\varepsilon)/\omega_{bi}$] decreases, a sawteeth crash induces the onset of the 3/2 mode as shown in Fig. 3(a).

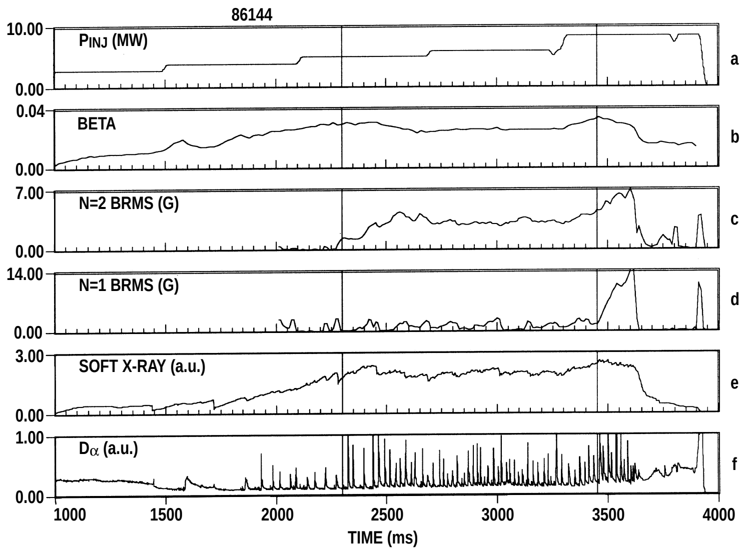

Fig. 2. Discharge #86144. (a) Injected beam power, (b) β from MHD reconstruction code EFIT, (c) rms amplitude of n = 2 rotating tearing mode (m = 3, n = 2), (d) rms amplitude of n = 1 rotating tearing mode (m = 2, n = 1), (e) central soft x-ray chord showing periodic sawteeth, and (f) D_α photodiode signal at divertor showing frequent edge localized modes. Note onset of 3/2 mode at 2250 rms and 2/1 mode at 3450 ms.

Upon further heating, β_θ again slowly rises, ν_* decreases and an ELM induces the 2/1 mode as shown in Fig. 3(b).

If $\Delta' < 0$, the neoclassical stability depends on the size of the seed perturbation w_{seed} relative to critical islands $w_d = (L_s/k_\theta)^{1/2} (\chi_\perp/\chi_{||})^{1/4}$ and/or $w_g = [g(\varepsilon, \nu_i)(L_q/L_p)/\varepsilon^{1/2}]^{1/2} \rho_{\theta i}$. For typical DIII–D parameters $w_d \approx 0.5$ cm and $w_g \approx 2.4$ cm compared to minor radius a = 61 cm. The metastable region of the modified Rutherford equation is shown as the shaded region in Fig. 4. If a seed island w_{seed} exceeds the critical island w_{crit}, the metastable state is destabilized and w_{seed} grows to saturated size w_{sat}. Otherwise w_{seed} decays away.

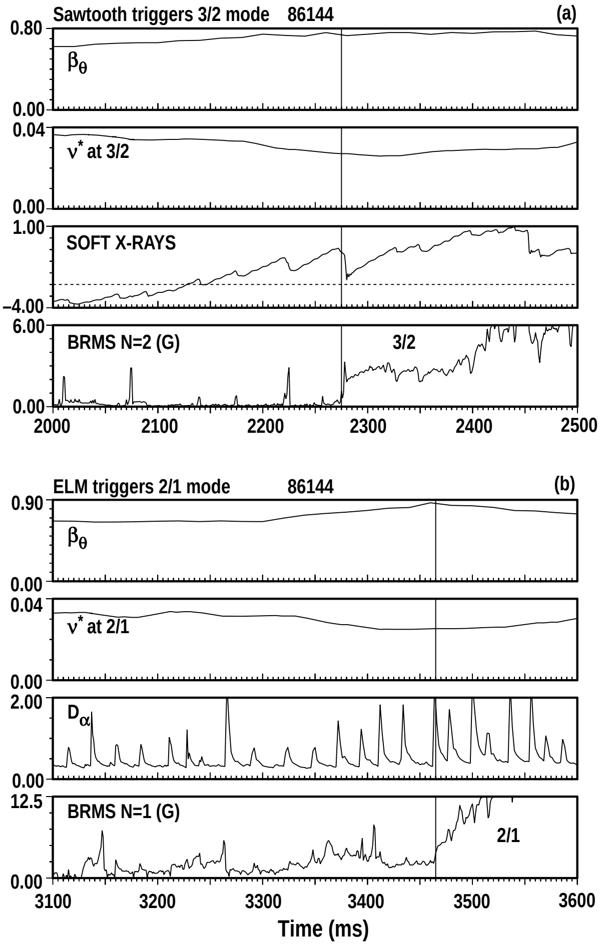

Fig. 3. (a) Correlation of a sawtooth crash (and 2/2 mode "gong") with the growth of a 3/2 tearing mode. (b) correlation of an ELM (and broad m/n "gong") with the growth of a 2/1 tearing mode.

As the neoclassical destabilization with beta depends on collisionality in different ways, empirical fits of critical beta for onset of 3/2 or 2/1 tearing were made to ν_*, ρ_*, etc. for as wide a range of variables as possible. The database of discharges at the onset of 3/2 tearing or 2/1 tearing scans B_T = 0.9–2.1 T at I_p = 0.65–1.5 MA with $q_{95} < 4$, $\bar{n}_{14}$ = 0.26–0.82, with critical β = 1.73–5.16%. The radial scale lengths at q=m/n for q, T_e, and T_i at the 3/2 and 2/1 mode onsets, respectively, do not vary significantly. The H–mode core density profile is fairly flat in all cases. For the 3/2 mode onset, the mean $L_q/a = 0.55 \pm 0.05$, $L_{Te}/a = -0.39 \pm 0.06$, and $L_{Ti}/a = -0.33 \pm 0.03$. The mean Δ' using the high m approximation [4] is -9.4 ± 1.5 m^{-1}. For the 2/1 mode onset, the mean $L_q/a = 0.40 \pm 0.03$, $L_{Te}/a = -0.41 \pm 0.08$, and $L_{Ti}/a = -0.38 \pm 0.10$. The mean Δ' using the high m approximation is-8.0 ± 1.8 m^{-1}. Thus the principal experimental variables for the tearing mode destabilization are beta, collisionality, and gyroradius. A fit to $\beta_{crit} \sim \nu_*^x \rho_*^y$ was done in the spirit of dimensionless transport scaling and the dependence on the local parameters of the soft 3/2 tearing mode beta limit is shown in Fig. 5(a). For the 3/2 mode, the range in ν_* is only 3.1 and in ρ_* only 1.4. At low B, the 2/1 mode turns on first and the discharges disrupt. For the onset of the 2/1 mode shown in Fig. 5(b), ν_* varies a factor of 16 while ρ_* varies a factor of 1.6. The ρ_* dependence is 0 ~ 1/3 within the uncertainty. The scaling with $\nu_i/\varepsilon\omega_{*e}$ which is more relevant for the ω^* model instead of ν_* was almost as good as for ν_*.

Similar and even lower collisionality discharges in DIII–D were successfully run for 1.5 seconds at $\beta_N = 3$ without tearing modes by applying weak early beam heating in the current rampup so as to maintain $q(0) \gtrsim 1$ in the I_p flattop, with no sawteeth. Removing the sawteeth

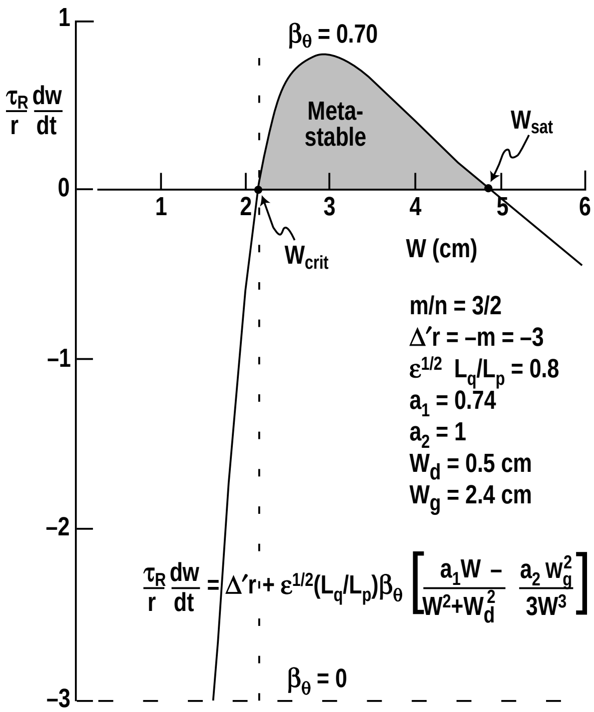

Fig. 4. Modified Rutherford equation for island growth versus island size. If seed w_S < critical size w_C, island decays. If seed w_S > critical size w_C, island grows to size w_{sat}

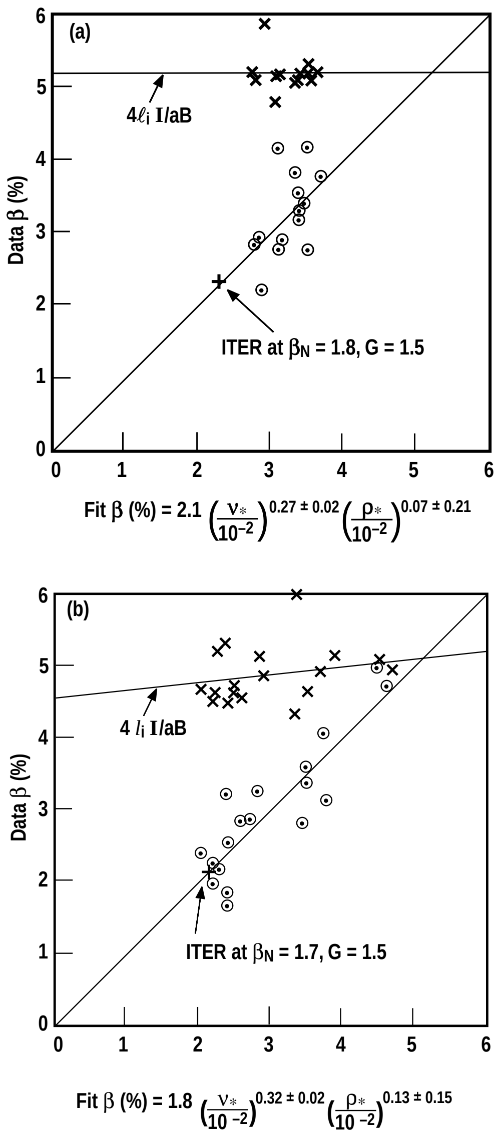

Fig. 5 (a) Onset of 3/2 tearing (⊙) in DIII–D fitted to <u>*local*</u> *parameters. (b) Onset of 2/1 tearing (⊙) in DIII–D fitted to* <u>*local*</u> *parameters. Expected ITER beta limit is also shown (+) as well as expected ideal limit (×).*

perturbation w_{seed} can explain avoiding the 3/2 metastable mode but surprisingly the ELMs remained large but did not destabilize the 2/1 mode.

Replacing the perturbed bootstrap current “missing“ in the island O-point by radially localized ECCD has been proposed to suppress and/or stabilize the modes [8]. Experiments to evaluate this stabilization are planned for this year on DIII–D.

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