PRACTICAL BETA LIMIT IN ITER-SHAPED DISCHARGES IN DIII–D AND ITS INCREASE BY HIGHER COLLISIONALITY[*]

R.J. La Haye, J.D. Callen,[†] S. Deshpande,[Δ] T.A. Gianakon,[†] C.C. Hegna,[†] S. Jardin,[Δ]
L.L. Lao, J. Manickam,[Δ] D.A. Monticello,[Δ] A. Pletzer,[#] A.H. Reiman,[Δ] E.J. Strait,
T.S. Taylor, A.D. Turnbull, and H.R. Wilson[§]

General Atomics, P.O. Box 85608, San Diego, California 92186-9784

Successful steady-state tokamak operation requires operating at the highest possible beta while avoiding both ideal and resistive MHD instabilities which reduce confinement and induce disruption. 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 is found to be limited not by ideal modes but by the onset of resistive MHD instabilities. 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. 1) 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 usually induces a disruption. (Plasmas are neutral beam heated ELMing H–mode with sawteeth; the safety factor q_{95} is just above 3.)

Higher stable beta in these long-pulse discharges is successfully run by operating at higher density $\bar{n}$ and higher collisionality $\nu^* \equiv \nu_{ei}/\varepsilon\omega_b \sim \bar{n}^3\ R/\beta^2\ B_T^4$, which suppresses both the 3/2 and 2/1 mode onsets. Density $\bar{n}$ is the control parameter varied by gas puffing in these ELMing H–mode discharges. The onset of the 3/2 mode occurs at $\beta_N = 3.74\ G^{0.70} \sim \nu^{*0.44}$ with the normalized beta $\beta_N \equiv \beta\ (\%)/[I_p/aB_T\ (\mathrm{MA/m/T})]$ and the normalized density $G \equiv \bar{n}\ (10^{14}\ \mathrm{cm}^{-3})\ \pi a^2/I_p$. The onset of the 2/1 mode occurs at slightly higher beta, $\beta_N = 3.79\ G^{0.59} \sim \nu^{*0.32}$, and approaches the expected ideal limit of $\beta_N \approx 4\ \ell_i \approx 3.8$ at $G \approx 1$ (Fig. 2) where ℓ_i is the internal inductance. Successful quasi-steady-state operation without limiting modes at $\beta_N \approx 3$ was achieved with $G \approx 0.65$.

Two possible means have been identified as the cause of the onset of these instabilities. Resistive tearing modes that occur at rational surfaces q = m/n cause reconnection into islands of full width w. The island onset and growth can be due to either free energy from an unstable current J_ϕ profile ($\Delta' > 0$) or to a helical bootstrap current which amplifies a seed island ($\Delta' < 0$). These mechanisms are tested using accurate MHD equilibria reconstructions with the code EFIT [1] using the external magnetics, local measurements of the internal poloidal field with the 16 channel motional Stark effect diagnostic and the measured pressure profile.

Resistive MHD analysis of Δ' is computed from EFIT both by an analytical formula [2] and by the PEST-III code [3]. Resistive non-linear MHD analysis is computed on these equilibria with the PIES code [4]. Any changes to Δ' with beta and density may be due to current density profile modification by central beam-driven current and edge bootstrap and inductive currents. To explain the onset of both the 3/2 and 2/1 rotating resistive modes at higher beta and/or lower density (collisionality) would require steepening of the local grad J_ϕ at both q = 3/2 and 2/1 in a plasma where sawteeth keep the axial $q \approx 1$ and the edge q_{95} is held fixed, which is not clearly supported by the data.

However, an explanation of the experimental results can be made using the neoclassical bootstrap current destabilization of a seed island for $\Delta' < 0$, i.e. otherwise stable. This effect

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[*] Work supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114 and partly funded by the UK Department of Trade and Industry and EURATOM.

[†] University of Wisconsin, Madison, Wisconsin.

[Δ] Princeton Plasma Physics Laboratory, Princeton, New Jersey.

[#] CRPP-EFP, Lausanne, Switzerland.

[§] UKAEA Fusion, Culham, Abingdon, Oxfordshire OX14 30B, United Kingdom.

is increasingly more destabilizing with beta as the modified Rutherford equation for island growth is given by $(\mu_0/1.22\ \eta_{nc})\ dw/dt = \Delta' + \varepsilon^{1/2}\ \beta_\theta\ (L_q/L_p)\ [w/(w^2 + w_c^2)] - \rho_{\theta i}^2\ \beta_\theta\ g(\varepsilon)\ (L_q/L_p)^2/w^3$ where the second term on the RHS is usually $(L_q/L_p > 0)$ destabilizing. Other MHD events such as sawteeth or ELMs often trigger the onset of the resistive modes, supporting the idea that they are neoclassically destabilized by a seed perturbation. The density/collisionality can enter (for $\Delta' < 0$) in either of two ways. In the "$\chi_\perp/\chi_{||}$" model [5], 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_c is an increasing function of density/collisionality. In the "ω_*" model [6], the toroidally enhanced ion polarization drift response of the plasma to the seed island due to inertial effects adds a stabilizing term to the modified Rutherford equation (the third term on the RHS) which dominates at small w. It has a collisional factor $g(\varepsilon) = \varepsilon^{3/2}$ for $\nu_i/\varepsilon\omega_{*e} \ll 1$ and $g(\varepsilon) = 1$ for $\nu_i/\varepsilon\omega_{*e} \gg 1$ that can increase the critical island size a factor of 2–3 since our density scan causes $\nu_i/\varepsilon\omega_{*e}$ to range from 0.05 to 4.

As the higher field, larger ITER device is expected to have both lower ν^* and ρ^*, extrapolation to ITER requires understanding of which of the neoclassical threshold mechanisms dominates, how β_{crit} scales with ν^* (and ρ^*), and how the necessary seed perturbation island (particularly from sawteeth and ELMs) for the neoclassical destabilization scales. An interesting possibility is whether a higher stable beta can be obtained by operating at $q > 1$ to eliminate sawteeth perturbations or with negative magnetic shear which is neoclassically stabilizing for modes inside the shear reversal region $(L_q/L_p < 0)$.

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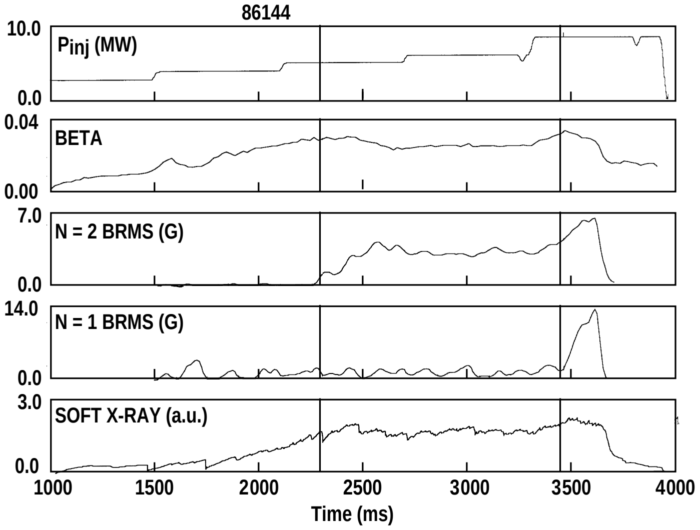

Fig. 1. Low-n resistive modes turn on as beta is slowly raised.

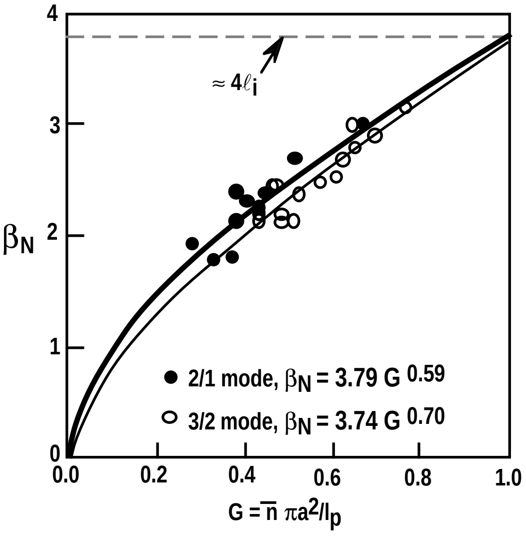

Fig. 2. Thresholds for 3/2 and 2/1 modes.