Polarization Current and the Neoclassical Tearing Mode Threshold in Tokamaks;Comparison of Experiment With Theory* EX

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Neoclassical tearing mode islands are one of the main causes of reduced performance at high β_θ in both standard ELMy sawteething H–mode and in advanced tokamaks. Instability threshold data from a multi-machine database are consistent with recent theory where polarization current provides the threshold. Detailed mode propagation measurements in DIII–D also support the present theory. Confirmation of the polarization threshold is a key issue for understanding and predicting the onset of beta limiting neoclassical tearing modes in both conventional and advanced tokamaks and for extrapolation to the beta limit of reactor-grade tokamaks

Tokamak plasmas are metastable to neoclassical tearing modes (NTMs) in that the plasma must usually be perturbed beyond a threshold so that the helically perturbed bootstrap current can cause the mode to grow. The leading candidate for the threshold mechanism [1] is the helical polarization/inertial current which arises from mode propagation in the E_r=0 guiding center frame of plasma flow at frequency $\delta\omega$. A threshold island width w_{thresh} is predicted (Fig. 1), which is proportional to the ion banana width $\varepsilon^{1/2}\rho_{\theta i}$ with a coefficient that increases several times if the ion collision frequency ν_i/ε exceeds $\delta\omega$, and also depends on $\delta\omega$. For example, the threshold would be zero for $\delta\omega$=0 (thus no polarization current) or for $\delta\omega=\omega_{*i}$, the ion diamagnetic drift frequency. The original theory predicted propagation in the electron drift direction which would be stabilizing, i.e., a threshold for $\delta\omega$<0. However, subsequent reappraisal of the theory in a sheared slab geometry [2] identified an additional

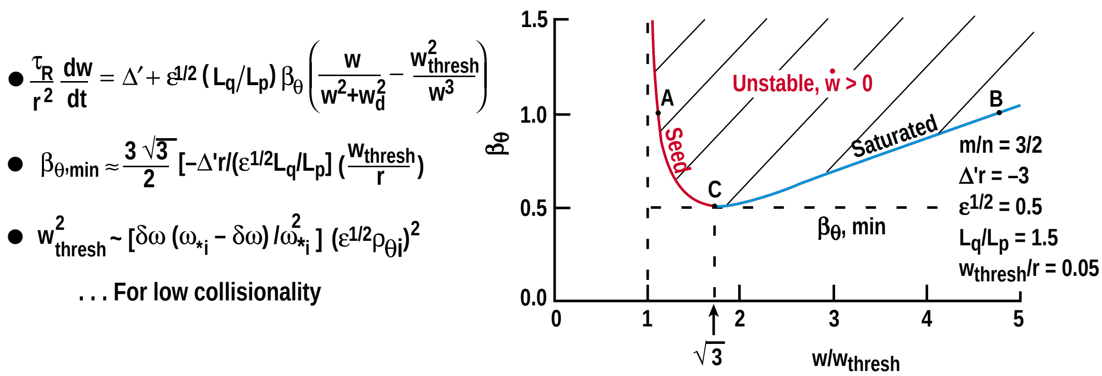

Fig. 1. Helically perturbed bootstrap current can excite neoclassical tearing mode. Unstable region is bounded by dw/dt = 0 from the modified Rutherford equation shown on the left.

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contribution to the helically perturbed polarization/inertial current which reverses its overall effect on island stability leading to a threshold predicted for $0<\delta\omega<\omega_{*i}$.

Threshold scaling data is consistent with predictions of the polarization current theory which (Fig. 1) yields a <u>minimum</u> critical β_θ <u>below</u> which the helically perturbed bootstrap current is too small to excite NTMs (assuming that the flow $\delta\omega/\omega_{*i}$ yields a stabilizing threshold). This would give a linear scaling of critical β_N ($\propto\beta_\theta$) with ρ_{i*} ($\propto \rho_{i\theta}/a$) in the low collisionality regime from the polarization threshold theory. A database from similar regimes [high confinement H–mode with periodic edge localized modes (ELMs) and periodic central sawteeth] was compiled from the tokamaks ASDEX Upgrade (AUG), DIII–D and JET in lower single-null divertor configuration with $q_{95} \gtrsim 3$. Such a $\beta_{Ncrit}\propto\rho_{i*}$ is indeed observed experimentally in tokamaks for the m/n=3/2 NTM induced by a sawtooth crash as shown in Fig. 2 from contour <u>fits of experimental data</u>. The observed weak collisionality dependencies are explained to arise from either the transition to the larger threshold regime or to a decreasing seed island regime [3].

Detailed measurements in DIII–D of mode propagation in the E_r=0 frame are also consistent with a polarization current threshold. DIII–D has an outstanding suite of diagnostics to help resolve physics issues: among them are (1) state-of-the-art 35 channel MSE poloidal field diagnostic for MHD equilibrium reconstruction using EFIT (with E_r correction) for precise location of q=m/n surfaces and (2) fast time resolution (0.5 ms) CER

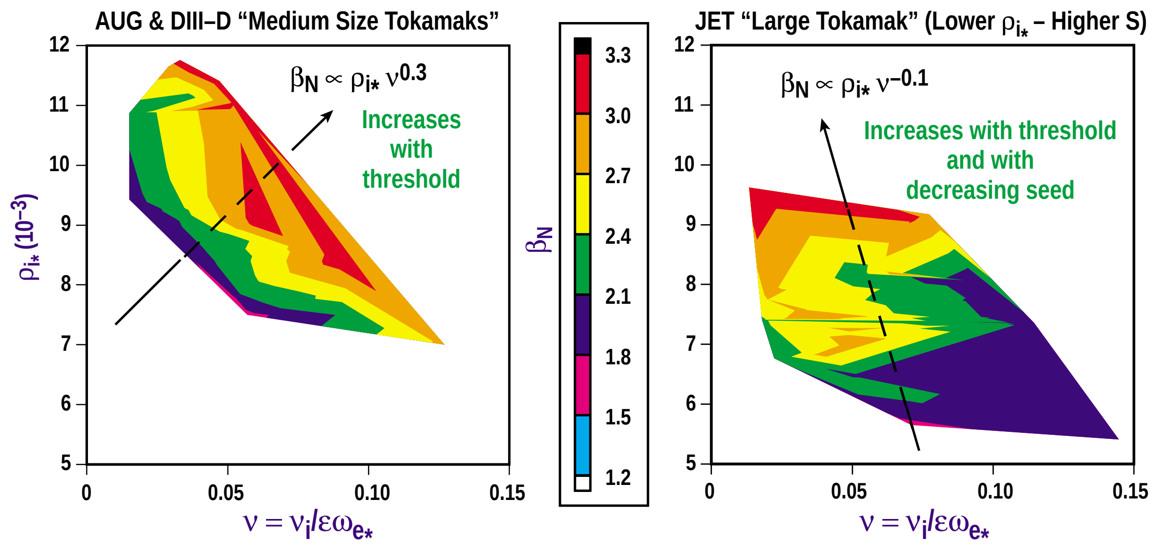

Fig. 2. Contour plots of critical β_N for m/n = 3/2 NTM from <u>fits of experimental data</u>.

diagnostic of E_r and T_i at a given surface. The key theoretical parameter at issue of $\delta\omega/\omega_{*i}$ is measured for an m/n=5/4 tearing mode before and for m/n=5/4, 4/3 and 3/2 tearing modes after a sawtooth crash which acts as the seed for the onset of 4/3 and 3/2 tearing modes, the 3/2 mode eventually growing to a much larger amplitude. <u>All of these modes have $\delta\omega/\omega_{*i}$~0.5 consistent with a stabilizing polarization threshold according to the most recent theory</u> (including the additional contribution). As the 3/2 NTM grows following the sawtooth crash, the mode propagation remains unchanged ($\delta\omega/\omega_{*i}$~0.4), independent of amplitude, from the first observation following the sawtooth crash, a time short compared to the tearing time τ_{tear}, to times much longer than τ_{tear}. Improved understanding of the NTM physics, including the polarization threshold, should allow prediction of the onset in future devices and the need for remedial measures such as radially localized rf current drive.

[1] H.R. Wilson, *et al.*, Phys. Plasmas **3**, 248 (1996).
[2] Waelbroeck, F., Connor, J.W., Wilson, H.R., *et al.*, private communication 1999.
[3] R.J. La Haye, *et al.*, Proc. 26th Eur. Phys. Soc. Conf. on Controlled Fusion and Plasma Physics, Maastricht, (1999) 1209.