Multi-Device Scaling of Neoclassical Tearing Mode Onset with Beta*

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The islands from tearing modes driven unstable and sustained by helically perturbed neoclassical bootstrap current at high beta are often the practical limit to long-pulse, high confinement tokamak operation [1]. In order to predict this beta limit for reactor grade tokamaks, a multi-device database has been assembled of the onset of neoclassical tearing modes (NTM) in Asdex-Upgrade, DIII–D and JET. The discharges studied are ELMy H–mode single-null divertor (SND) at $q_{95} \gtrsim 3$ with m/n=3/2 NTM induced by sawteeth (m/n=1/1 and 2/2). For a classically stable tearing mode, $\Delta' < 0$, the perturbed neoclassical bootstrap current, proportional to beta poloidal β_θ, can induce destabilization if β_θ exceeds a critical value $\beta_{\theta c} \approx (-\Delta' r)(w_s/r)\big/\left(\varepsilon^{1/2} L_q/L_p\right)\big/\left(1 - w_{th}^2/w_s^2\right)$ [2,3], Here w_s is the "seed" island width which must exceed a "threshold" island width w_{th}, i.e. the NTM is destabilized for $w_s > w_{th}$ and $\beta_\theta > \beta_{\theta c}$. Scaling or extrapolation to a reactor grade tokamak requires understanding of the scaling of both w_s and of w_{th}. If w_s decreases faster than w_{th} decreases, with ρ_{i*}, for example, then $\beta_{\theta c}$ can increase as the term $1 - w_{th}^2/w_s^2$ becomes smaller. The relative threshold island width from the polarization/inertial model [4] scales as $w_{th}/r \propto \rho_{i*} g^{1/2}(\varepsilon, \nu)$ where $g(\varepsilon, \nu)$ is a function of collisionality $\nu = \nu_i/\varepsilon\omega_{e*}$, $g = 1$ at $\nu \ll 1$ and $g = \varepsilon^{-3/2} \gg 1$ at $\nu \gg 1$. The relative seed island scaling is taken as $w_s/r \propto S^{-\alpha}$ (with α determined from fits to the experimental data) allowing for the dynamics of geometrically coupled perturbations [1,5]. The magnetic Reynold's number scales as $S \propto \beta_N^{1/2}\big/\nu\rho_{i*}^3$. Here $\beta_N = \beta/(I/aB)$ and $\beta_N \propto \beta_\theta$ for fixed shape and q_{95}. Thus at low ν, $w_s/w_{th} \propto S^{-\alpha}\big/\rho_{i*} \propto \rho_{i*}^{3\alpha-1}\nu^{\alpha}\big/\beta_N^{\alpha/2}$ and the scaling with ρ_{i*} of w_s/w_{th} and thus $\beta_{\theta c}$ depends critically on whether $3\alpha - 1 > 0$ or not. Comparison to experimental data gives best fits for $\alpha \approx 1/3$–$2/5$ and suggests that JET (lower ρ_{i*} and higher S values than in Asdex-U or DIII–D) is in a regime where the critical β_N/ρ_{i*} increases with higher S and lower collisionality rather than in a regime where β_N/ρ_{i*} increases with higher collisionality (Asdex-U and DIII–D). The full size ITER has comparable ν and β_N as existing devices but a factor of at least five lower ρ_{i*}. Thus, the stabilizing $w_{th}/r \sim \rho_{i*}$ is much smaller, but so is the destabilizing $w_s/r \propto S^{-\alpha} \propto \rho_{i*}^{3\alpha}$. Uncertainty in α yields a predicted critical $\beta_N \approx 0.5$ for $\alpha = 1/3$ due to $w_s/w_{th} \neq f(\rho_{i*})$ but stability at $\beta_N = 2.5$ for $\alpha = 2/5$ if w_s/w_{th} decreases as $\rho_{i*}^{1/5}$.

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