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NONLINEAR NEOCLASSICAL TEARING MODE SIMULATIONS IN TOROIDAL GEOMETRY

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In a future large tokamak, the growth of neo-classical tearing modes (NTM's) is a major obstacle for the achievement of the confinement conditions required by a fusion plasma. Their control is therefore a crucial problem in a machine like ITER (International Thermonuclear Experimental Reactor), and requires a precise understanding from a theoretical point of view. Although progress has been made in the past years in controlling their dynamics with current drive systems, i.e. the NTM dynamics observed for large islands is well described by the generalized Rutherford equation [1] including curvature, bootstrap and polarization effects, several issues remain unclear, such as e.g. the physics of the onset of the NTM's or the nonlinear saturation mechanism. In a previous work, we have shown theoretically that in the small island regime, the curvature term introduces a finite threshold for the nonlinear destabilization of tearing modes without bootstrap current. This result was confirmed numerically by toroidal full MHD simulations including parallel and perpendicular transport effects with the XTOR code [2].

In the present work, the robustness of this finite nonlinear threshold is checked numerically for NTM's in full toroidal geometry with XTOR when bootstrap effects are included. For this purpose, a bootstrap term proportional to the pressure gradient was implemented in XTOR. The equations solved numerically are the same as in Ref.[3], except for Faraday, which was generalized to

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times \eta(\mathbf{J} - \mathbf{J_{boot}}) \tag{1}$$

with $\mathbf{J_{boot}}(t) = (\nabla p)_r(t)/p'(t=0)\mathbf{J_{boot}}(t=0)$. Both the quantities at $t = 0$ are provided by the CHEASE equilibrium code. Numerical results with XTOR are compared with the generalized Rutherford equation without polarization current effects [2, 4],

$$\frac{\tau_r}{1.22}\frac{dw}{dt} = \Delta'\left(1 - \frac{w}{w_{sat}}\right) + \frac{6.35 D_R}{\sqrt{w^2 + 0.65 w_d^2}} + 6.35\frac{R_o q}{B_o s_s} f_{bs} J_{boot}\frac{w}{w^2 + (1.8 w_d)^2} \tag{2}$$

where $w_d = 2\sqrt{2}\left(\frac{\chi_\perp}{\chi_{//}}\right)^{1/4}\left(\frac{r_s R}{ns}\right)^{1/2}$ is a diffusion length scale, $s = rq'/q$ is the magnetic shear at the resonant surface $r = r_s$, R is the major axis of the torus, n is the toroidal mode number of the mode and q is the safety factor. J_{boot} is the bootstrap current density, and D_R is the resistive interchange parameter. In the large aspect ratio limit, $D_R = 2(q^2-1)rp'/(s_s^2 B_o^2)$, and for tearings with $q > 1$, $D_R < 0$. In slab geometry, $J_{boot} = 1.46p'q\sqrt{A_s}/B_o$ [4]. In our numerical study, we have used D_R and J_{boot} computed by the CHEASE equilibrium code [5].

In the following, we focus on the nonlinear destabilization mechanism with a parameter study done to determine the seed island size required to destabilize nonlinearly NTM's as a function of the diffusion length w_d. These results a compared with the predictions of eq.(2). For our parameter study, two equilibria are used. Both are linearly stable towards pure resistive MHD tearing modes at zero pressure for $n \in [1, 20]$, i.e. $\Delta' < 0$ at the resonant surfaces of these modes. The first equilibrium has a circular poloidal cross section, with aspect ratio $A = 2.56$, total poloidal beta $\beta_p = 1.0$, $q_0 = 1.9$. The second has ITER geometry, with $A = 3$, a plasma elongation and triangularity of 1.75 and 0.4, respectively, $\beta_p = 0.73$. Instead of $q_0 = 1$, as in the original equilibrium from the ITER database, the q profile is shifted keeping β_p constant using equilibrium scaling laws so that $q_0 = 1.25$. Both equilibria have a total bootstrap fraction of about 25%. Fig. 1

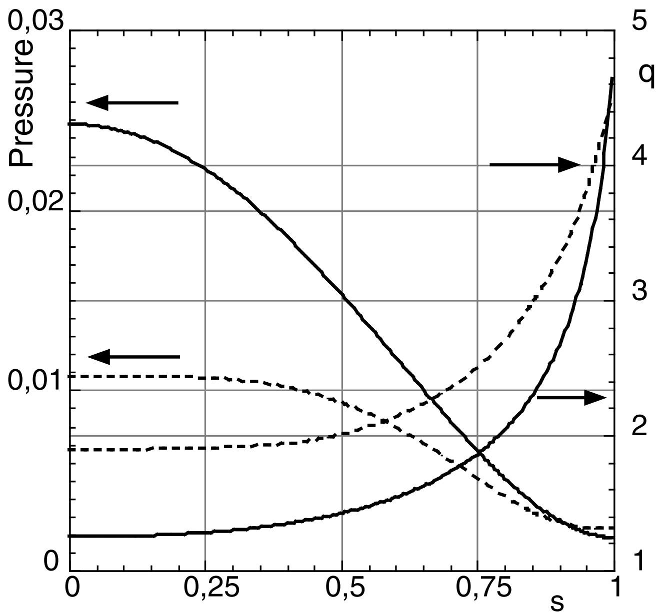

Figure 1: Equilibria pressure and safety factor profiles for **a)** the ITER (full curves) and **b)** the circular (dotted curves) case

shows the pressure and the q profiles for both equilibria. In the circular case, we have destabilized nonlinearly $m/n = 2/1$ NTM's, whereas in the ITER case, $m/n = 2/1; 3/2$ and 4/3 NTM's are considered. For all cases, two ratios of parallel to perpendicular thermal diffusion coefficients are used, $\chi_{//}/\chi_{\perp} = 6.25.10^6$ and $\chi_{//}/\chi_{\perp} = 10^8$, both with $\chi_{\perp} = 3.10^{-6}$.

All the simulations with XTOR in the following are performed with a Lundquist number $S = 10^7$. Fig.2 shows a generic behavior of XTOR near the nonlinear unstable point of a $m/n = 4/3$ NTM. For a seed island with a width w smaller than the value required to destabilize the NTM, here about 2% of the minor radius of the torus, the mode is not growing, whereas above this threshold, the NTM island size increases rapidly. Fig.2 gives also an estimation of the accuracy of the threshold computed with XTOR, typically 15 to 20%

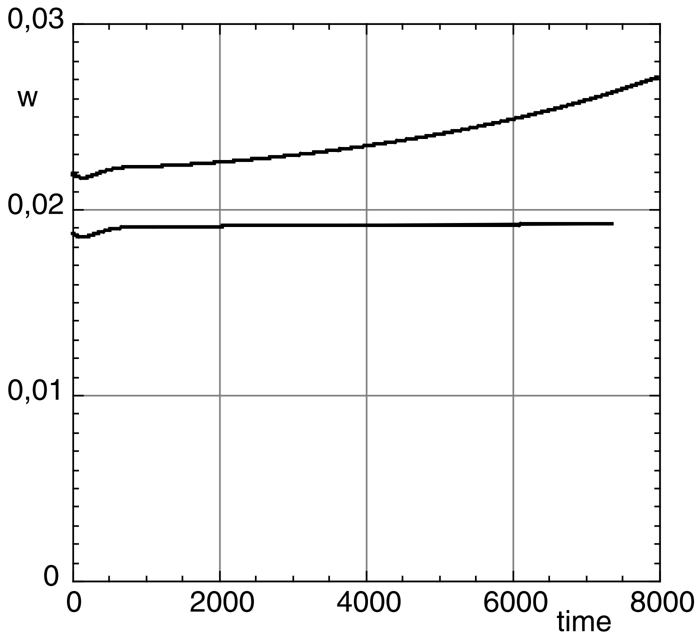

Figure 2: $m/n = 4/3$ NTM magnetic island size time evolution for the ITER case with $\chi_{\perp}/\chi_{//} = 10^{-8}$ with a seed island just above and below the nonlinearly unstable point.

The nonlinear thresholds w_c obtained with XTOR are compared with the prediction by Eq. (2) in Fig.3. The values obtained by XTOR are drawn on the horizontal axis, whereas the vertical axis represents the unstable point obtained with the right hand side (RHS) of Eq. (2). This RHS was evaluated here by supposing $\Delta' = 0$. The points labeled with (C) and (I) correspond to the circular and the ITER case, respectively. If two points are represented for one equilibrium, the one with the smaller values of w_c correspond to $\chi_{//}/\chi_{\perp} = 10^8$ and the one with the larger values of w_c to $\chi_{//}/\chi_{\perp} = 6.25.10^6$. All the ITER cases are also computed with $f_{bs} = 0.4$, but only the $m/n = 4/3$ NTM is nonlinearly unstable.

A good match between full scale MHD simulations and Rutherford's equation would lead to a curve of slope 1 in Fig.3. Clearly, the slope of the linear interpolation of the points in Fig.3 shows a strong departure from this value. The slope is indeed close to 3. Work is under way to clarify this issue.

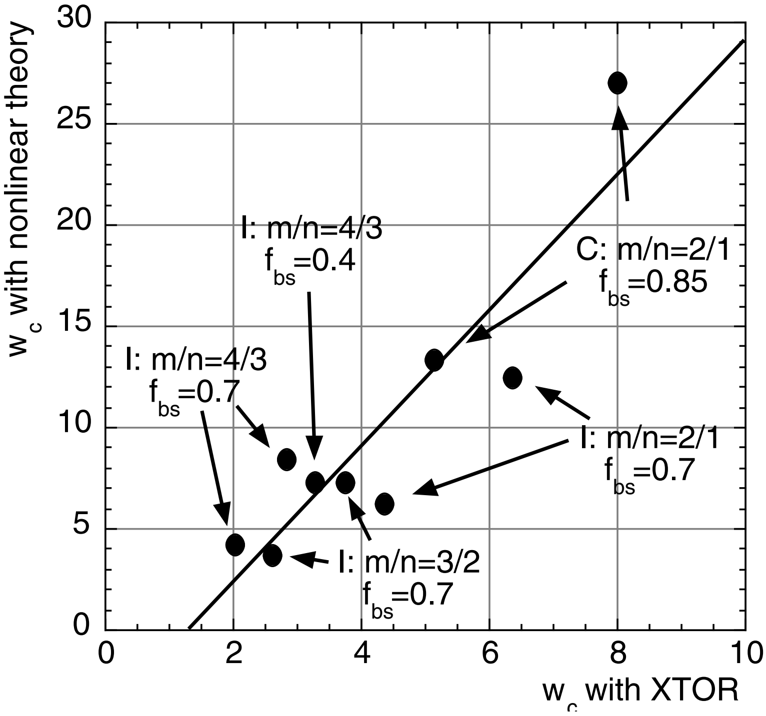

Figure 3: Nonlinear NTM marginal stability points for the circular (C) and the ITER (I) equilibria for different mode numbers, f_{bs} values and $\chi_{\perp}/\chi_{//}$ ratios.

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