Full MHD simulations of multiple NTM's in ITER like plasmas

H. Lütjens, J.-F. Luciani

Centre de Physique Théorique, UMR 7644 du CNRS, Ecole Polytechnique, 91128 Palaiseau

cedex, France

Introduction

The simultaneous presence of several NTM's has been observed in many tokamaks, eg. ASDEX-Upgrade, JET or TCV. In certain discharges, nonlinear couplings between low n NTMs, mostly $m/n = 3/2$ and $4/3$ were observed [1, 2], leading to the stabilization of one of the modes when the other grows. In others, internal kinks seem to be linked to the stabilization and the destabilization of these NTM's. The role of the internal kink is not yet clarified. It can act on the stability properties of the NTM's via different effects (seed island generation, harmonic coupling, equilibrium profile effects, etc...).

Figure 1: Safety factor and pressure profiles of ITER equilibria.

The present work is only devoted to the interaction between $m/n = 3/2$ and $4/3$ NTM's without the presence of an internal kink. For this purpose, we use a ITER-like equilibrium with $A=3$, $\kappa=1.75$ and $\delta=0.3$. The q_0 of the original ITER profile was shifted to 1.25 using equilibrium scaling laws to avoid $q = 1$ (Fig. 1).

The simulations were performed with the XTOR code in full toroidal geometry. It solves the extended MHD equations (with no polarization current effects)

$$\partial_t \mathbf{v} = -\mathbf{v}.\nabla\mathbf{v} + \mathbf{J} \times \mathbf{B} - \nabla p + \nu\nabla^2\mathbf{v}$$

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

$$\partial_t p = -\Gamma p\nabla\mathbf{v} - \mathbf{v}.\nabla p + \nabla\chi_\perp\nabla p + \mathbf{B}.\nabla[\chi_{||}(\mathbf{B}.\nabla p)/B^2] + H$$

The initial resistivity profile is given by $E_\Phi = \eta(J_\Phi - J_{\Phi,bootstrap})(t=0) =$ constant and the resistivity evolves according to $\eta(t) \propto p^{-3/2}(t)$ (Spitzer's law). The heat source $H = -\nabla\chi_\perp\nabla p_{eq}$ and the bootstrap current $\mathbf{J_{boot}(t)} = f_{bs}\|\mathbf{J_{boot,eq}}\|(\nabla p(t))_r/p'_{eq}\mathbf{B(t)}/\|\mathbf{B(t)}\|$ with equilibrium quantities by the CHEASE code. The parameters used here are $\chi_{//}/\chi_\perp = 10^8$, $\chi_\perp = 3.10^{-6}$, $\nu = 10^{-6}$ and $S = 10^7$.
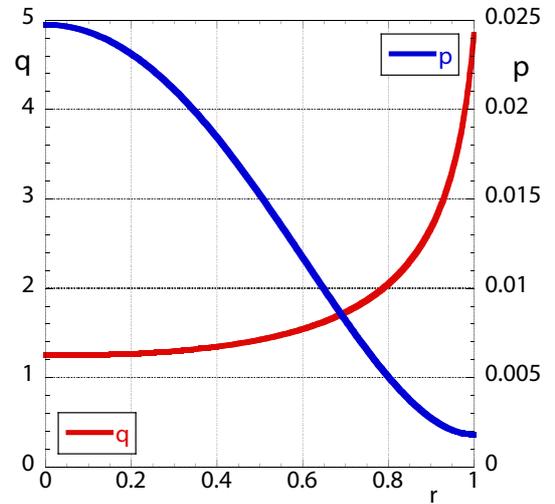
Multiple NTM simulations

Double $m/n = 3/2$ and $4/3$ NTM simulations were performed using XTOR with the q-profiles in Fig. 1 and several combinations of seed magnetic island sizes. As an example, the time evolutions of a $m/n = 3/2$ (red curve) and a $4/3$ (blue curve) NTM magnetic island size simultaneously destabilized by a large and a small seed island, respectively, are shown in Fig. 2.

When the $3/2$ NTM or the $4/3$ NTM is destabilized alone, it saturates at about 16% and 14% respectively and stays at this size when the simulation is prolonged in time. In single NTM simulations, only little magnetic field line stochasticity appears in the vicinity of the NTM island separatrice. Conversely, in the double NTM simulation in Fig. 2, the island sizes drop after the saturation of the NTM's. The two green arrows correspond to the two time slices where 3D views of the pressure and Poincaré plots of the magnetic field lines across a poloidal section of the torus are shown in Fig. 3. An inspection of Fig. 3 shows that the $3/2$ and the $4/3$ separatrices disappear between these two time slices. During the growth phase of both instabilities, high m and n is-
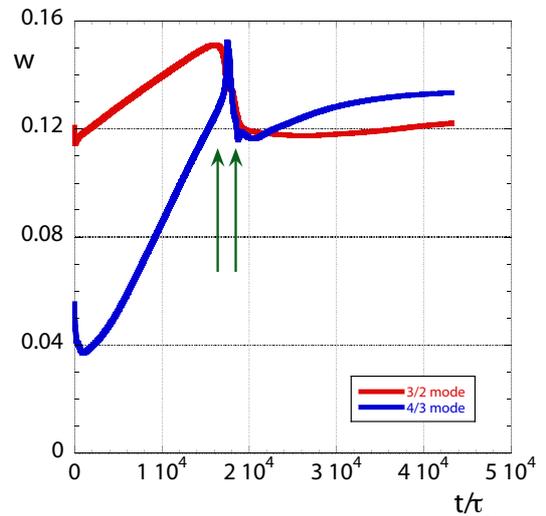

Figure 2: Time evolution of the $m/n = 3/2$ and $4/3$ magnetic island sizes. The green arrows indicate the times of the time slices of Fig. 3

land chains are generated just inside and outside of both NTM separatrices. These island chains overlap during the evolution, creating zones about both mode separatrices where the magnetic field is stochastic. Meanwhile, both NTM's grow, only leaving a very narrow region between the $3/2$ and the $4/3$ island chains where the magnetic field lines remain integrable. The moment where this region vanishes corresponds to the first green arrow in Fig. 2 and one can observe in Fig. 3 at $t = 16400\tau_a$ that separated $3/2$ and $4/3$ structures still exist. At this moment, the corresponding $3/2$ and $4/3$ islands still clearly appear on the 3D view of the pressure. Between $t = 16400$ and $t = 18400\tau_a$ (second green arrow in Fig. 2), stochastic coupling between both NTM's occur. Both NTM separatrices have merged and disintegrated. The entire annular zone covering both saturated NTM's, becomes stochastics except for very small $3/2$ and $4/3$ remainders (see Poincaré plot at $t = 18400\tau_a$ in Fig. 3). Because of the large parallel thermal diffusion coefficient, the pressure in this entire zone drops, as can be observed in the second 3D view of the pressure in Fig. 3. Note that the pressure in the center of the plasma remains unchanged. It evolves with $\chi_\perp$ on a much slower scale time.

Time = 16405.7 τ_a

Time = 18423.5 τ_a

Time = 16405.7 τ_a ; $\Phi = 0.0°$
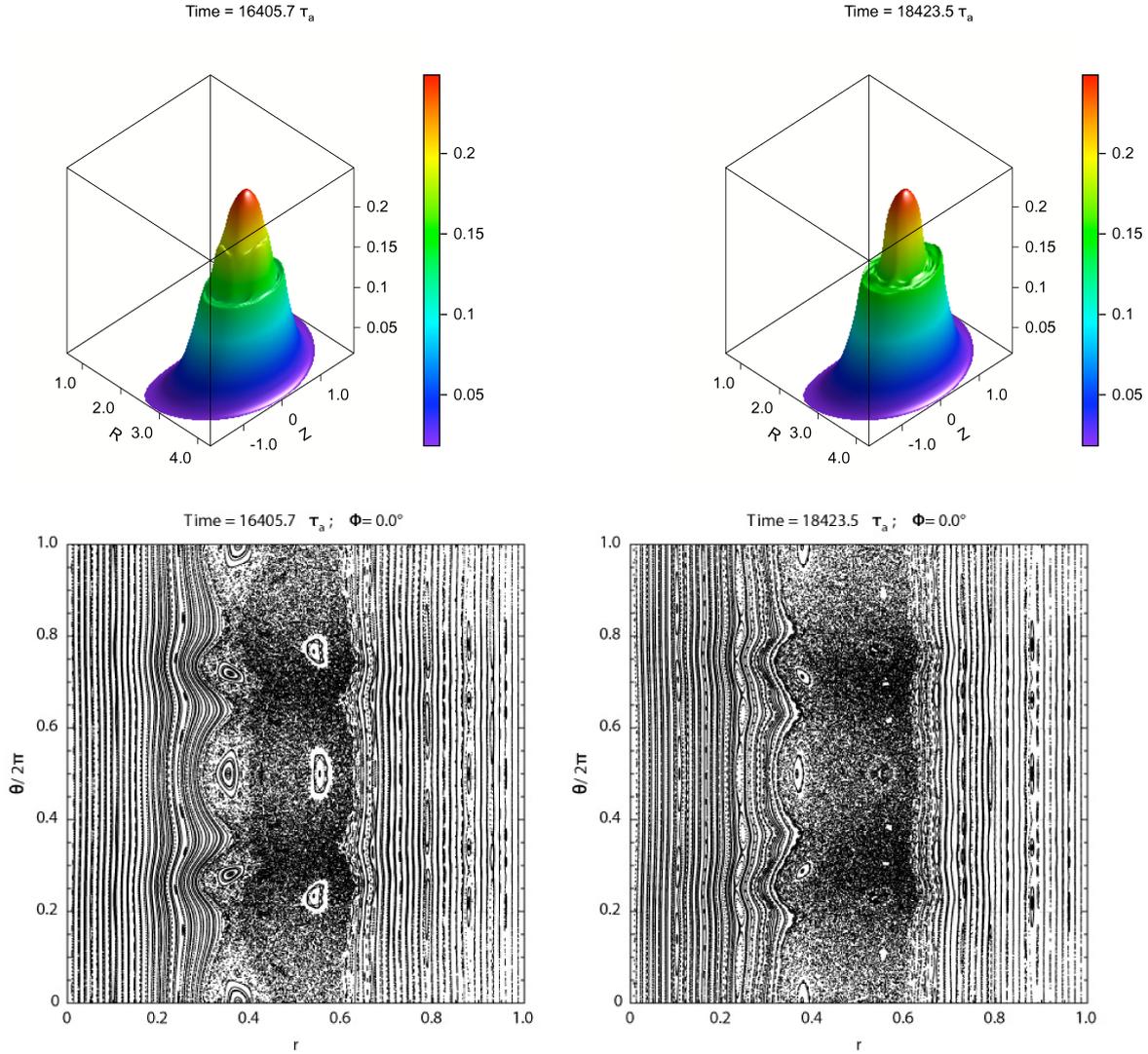
Time = 18423.5 τ_a ; $\Phi = 0.0°$

Figure 3: 3D view of pressure and the Poincaré plots of the magnetic field lines across a poloidal section of the torus before and after the pressure crash due to the stochastisation of the magnetic field in the entire zone covering both saturated NTM's

We emphasize that in all our multiple NTM simulations, even when starting with different initial seed islands or using a different equilibrium, we observe stochastic couplings between saturating NTM's. Thus this behavior seems to be generic in multiple NTM dynamics within the framework of the model solved by the XTOR code. Note also that in our simulations, no retroaction on the equilibrium q profile through the pressure evolution was observed. This retroaction occurs on a resistive time scale, which with $S = 10^7$ is much longer than the simulation times presented here.

Discussion

Numerical simulations of multiple NTM's have been done previously in reduced MHD [3]. Unfortunately, no Poincaré plots of the magnetic field are shown in that work, which makes a comparison very difficult. These plots a necessary to detect possible stochastic couplings between NTM's. Our results can however be compared to the so-called Frequently Interrupted Regime of NTM's, or FIR-NTM regime, first observed in ASDEX-Upgrade [1, 2]. In that regime, the growth of 3/2 and 4/3 NTM's present simultaneously in the plasma is interrupted periodically. This leads to drops in the NTM amplitude which occur on a time scale much faster than the resistive reconnection time. It is also observed that these drops prevent that the NTM's reach their saturation size. This behavior is similar to the one with our XTOR simulations in Fig. 2. Note that in the experiment, this dynamics in general seems to be accompanied by mode locking between the NTM's. Therefore the equations solved by XTOR approach reasonably this regime. In a more recent work on ASDEX-Upgrade, a careful reconstruction of the magnetic field line topology in the presence of a $m/n = 4/3$ and a $m/n = 3/2$ NTM was done [4]. In particular, Fig. 2 in Ref. [4] shows surprising similarities with our full MHD simulations. The Poincaré plot in our last time slide in Fig. 3 can directly be compared with Fig. 2 in Ref. [4].

The effect of the internal kink on this NTM dynamics might be considerable. First, during the internal kink saturation, harmonic modes of the internal kink can increase the stochastic couplings. Second, in the internal kink reconnection phase the equilibrium profiles are modified, in particular at the NTM resonant surfaces. This can change the stability properties of the NTM's. Numerical investigations including the internal kink dynamics will be presented in a future work.

References

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