Nonlinear Dynamics of Magnetic Islands Imbedded in Edge Tokamak Plasma Microturbulence

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In tokamaks, macro-scale MHD instabilities (magnetic islands) coexist with micro-scale turbulent fluctuations and zonal flows. Magnetic islands can, in particular, coexist with pressure driven instabilities such as interchange modes and/or turbulence. Several experiments and numerical studies report the coexistence of turbulence and MHD activities showing some correlated effects [6, 5, 2, 3]. We address here the multi-scale-nonlinear dynamics between macro-scale tearing instabilities and gradient pressure driven micro-instabilities (resistive interchange) by solving reduced MHD equations numerically.

We consider a two-dimensional slab plasma model that includes magnetic curvature effects and consists of cold ions and isothermal electrons. The basic evolution equations are [4],

$$\frac{\partial}{\partial t}\nabla_\perp^2\phi+\left[\phi,\nabla_\perp^2\phi\right] = \left[\psi,\nabla_\perp^2\psi\right]-\kappa_1\frac{\partial p}{\partial y}+\mu\nabla_\perp^4\phi, \quad (1)$$

$$\frac{\partial}{\partial t}p+[\phi,p] = -v_\star\left((1-\kappa_2)\frac{\partial\phi}{\partial y}+\kappa_2\frac{\partial p}{\partial y}\right)+\rho_\star^2\left[\psi,\nabla_\perp^2\psi\right]+\chi_\perp\nabla_\perp^2 p, \quad (2)$$

$$\frac{\partial}{\partial t}\psi = [\psi,\phi-p]-v_\star\frac{\partial\psi}{\partial y}+\eta\nabla_\perp^2\psi, \quad (3)$$

where the dynamical field quantities are ϕ, the electrostatic potential, p the electron pressure and ψ the magnetic flux. The equilibrium quantities consist of a constant pressure gradient and a magnetic field corresponding to a Harris current sheet model [1]. Equations (1-3) are normalized using the characteristic Alfvén speed v_A, the Alfvén time τ_A and a characteristic magnetic shear length scale $L_\perp$. Further, $\kappa_{i=\{1,2\}}$ include curvature and gradient pressure effects. μ is the viscosity, $\chi_\perp$ the perpendicular diffusivity, η is the plasma resistivity, $v_\star$ is the normalized electron diamagnetic drift velocity and $\rho_\star$ is the normalized Larmor radius. This model use in fact a reduced version of the four fields model derived in reference [7], neglecting parallel ion dynamics.

In a previous work [4], we have shown the existence of a bifurcation phenomenon in such dynamical systems that leads to an amplification of the pressure energy, the generation of an $E\times B$ poloidal flow and a nonlinear diamagnetic drift that affects the rotation of the magnetic island. However, in this previous study, the interchange branch was linearly stable and no small scale turbulence was impacting the island rotation. We obtained that the nonlinear dynamic of the magnetic island was the result of a competition between ExB and diamagnetic effects, the latter being dominant at high β. In this work we emphasize the role of the small scale interchange turbulence on the island rotation. The following parameter setting $\kappa_1 = 5$, $\kappa_2 = 0.36$, $v_\star = 0.01$, $\rho_\star = 0.003$, $\nu = \eta = \chi = 10^{-4}$, $\Delta' = 2$, $L_x = 2\pi$,$L_y = 5\pi$ leads to the coexistence on the resonant surface of a magnetic tearing and resistive interchange instabilities. The first occurs at at mode number $m = 1$ (wave number $k_m = m * 2\pi/L_y$) and the latter has a maximum growth rate at $m = 7$ with $\gamma_1/\gamma_7 \sim 0.75$. Owing to the scale separation of the instability, the resulting multiscale dynamics involve complex cascade phenomena which are out of the scope of this work. We focus on the nonlinear dynamics of the magnetic island.

In figure (1), we present the time evolution of the magnetic energy, of the kinetic energy and of the pressure energy. First there is a dominant linear growth of interchange modes around the resistive layer. Pressure fluctuations are the dominant contribution to the small scale instability as can be noted on the figure. Then, thanks to mode beating and tearing instability, the tearing $m = 1$ mode and the $m = 0$ one's become dominant and an magnetic island grows. They ultimately feed the other modes through cascade processes and a stationnary state is reached. To go further, we investigate the origin of the rotation. In figure (2), the poloidal position of the island versus time is plotted. Nonlinearly, we observe that the island propagation direction is reversed and the velocity of the island is strongly increased. If we compare with the time evolution of the model, we observe that the same characteristics are reproduced, up to a delay for the triggering of the nonlinear reversed rotation. In the absence of turbulence it was shown that resistive effect can be neglected. Here, it is obtained that this is not fully the case.

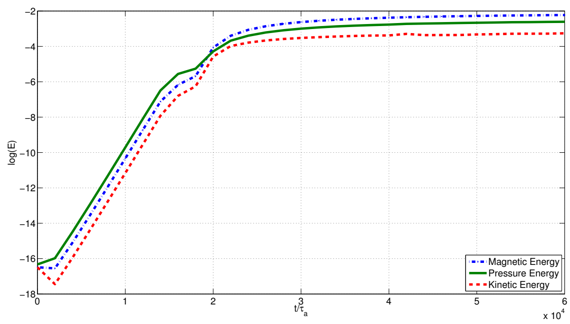
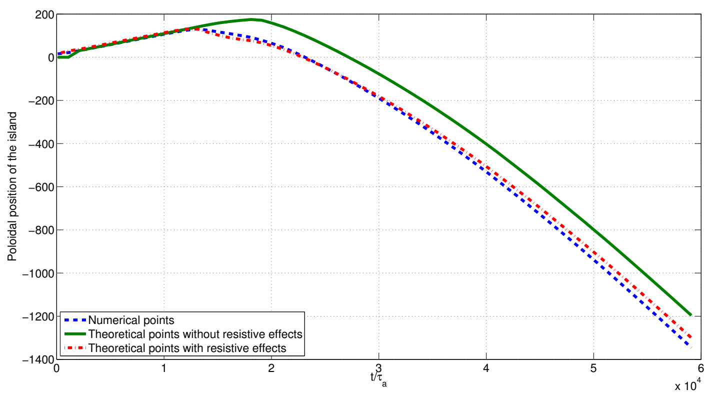


Figure 1: Time evolution of the energies

Following [4], we introduce a model to extract the dominant nonlinear contributions to the island rotation frequency ω. From



the Ohm's Law Eq.(3), we obtain

$$\omega = \omega^\star + \tilde{\omega}^\star + \tilde{\omega}_{E\times B} + L_{\psi_0} + L_\eta \ , \qquad (4)$$

where

$$\begin{aligned}
\omega^\star &= k_1 v^\star, \\
\tilde{\omega}^\star &= -k_1 \partial_x p_0, \\
\tilde{\omega}_{E\times B} &= k_1 \partial_x \phi_0, \\
L_{\psi_0} &= -Re\left(k_1 \psi_0' \frac{\phi_{k_1}(x) - p_{k_1}(x)}{\psi_{k_1}(x)}\right), \\
L_\eta &= Re\left(i\eta \frac{\left(\partial_x^2 - k_1^2\right)\psi_{k_1}(x)}{\psi_{k_1}(x)}\right) .
\end{aligned}$$

When the interchange modes are stables, the main nonlinear contributions to the rotation come from the nonlinear diamagnetique term $\tilde{\omega}$ and the nonlinear $E \times B$ flow, the resistive term L_η being insignificant. It can be checked in figure (3) that modes with interchange parity have a non zero contribution to L_η. We observe that in the range $t = [10000, 20000]$, this is the dominant contribution to the island rotation and is correlated with the change of direction of the island. In fact at larger time an direct cascade has occured and at all scale the dominant parity of the modes is the tearing one. This show that small scale turbulence can gouvern the island rotation direction, which would require a more extensive parameter dependance analysis. It also shows that small scale turbulence cannot be neglected when one consider the island rotation dynamics.

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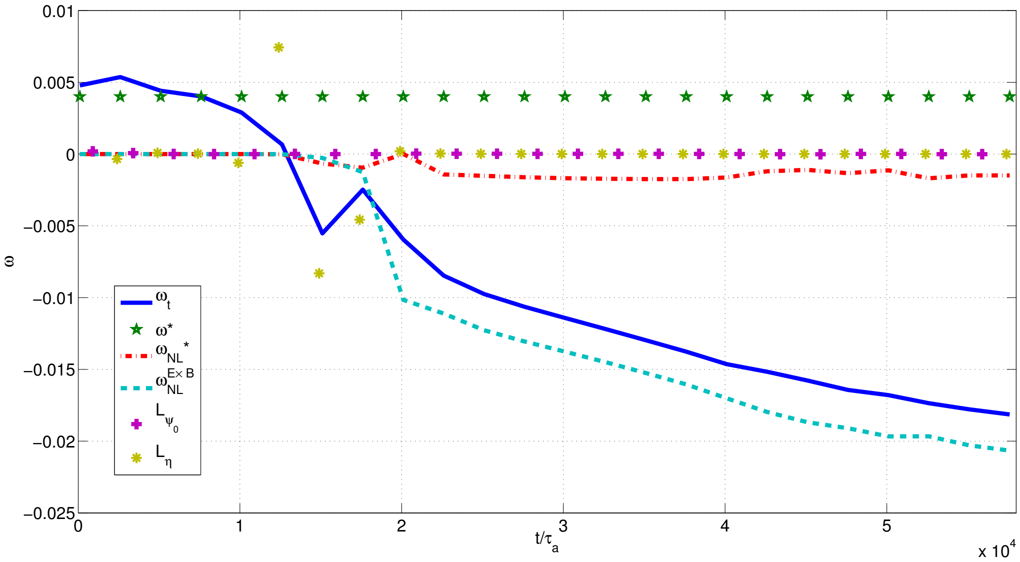

Figure 3: Contributions to the island frequency rotation versus time