J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Nonlinear dynamics of magnetic islands in presence of interchange turbulence

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(Received: 1 September 2008 / Accepted: 7 January 2009)

In this work, we study the interaction between a tearing mode and a pressure gradient instability (resistive interchange) by solving reduced MHD equations numerically. The numerical study shows existence of regimes where thetearing instability is driven by the pressure gradient. An interplay between the pressure and the magnetic flux controls the dynamics of the saturated state. A secondary instability, triggered by interchange unstable modes, produces convective cells which modify the nature of the magnetic island. The system reaches a new state where small scales are produced and the diamagnetic effect is strongly enhanced as well as the poloidal rotation.

Keywords: magnetic island, small scale turbulence, tearing instability, interchange instability, poloidal rotation

1. Introduction

In a tokamak, plasma confinement can be affected by instabilities. More precisely, at resonant surfaces, small scale turbulence can be observed and a strong MHD activity can be generated. The effects of these two mechanisms on the plasma confinement have been mainly investigated separately. However, usually, in a plasma, magnetic islands coexist with microturbulence. Several experiments report the coexistence of both small scale turbulence and MHD activities showing some correlated effects. For instance, microturbulence is observed in Large Helical Devices plasma [1] and MHD activities are observed in reversed shear plasmas with transport barriers related to zonal flows and microturbuence [2]. Moreover, it is well known that microturbulence produces large scale flows and zonal flows and the effect of these flows on the the island poloidal rotation is still an open question, even if previous works have been done [3], [4], [5], [6], [7]. In this work, we investigate the effect of a pressure gradient linked to an interchange like instability, on a magnetic island driven by a tearing instability. We also provide some insights on the origin of the nonlinearly generated island poloidal rotation.

2. Model

A reduced MagnetoHydrodynamic based model, where interchange and tearing instability mechanisms are present, is used [8]. Typically, it involves a set of coupled equations for the electrostatic potential ϕ, the pressure of the electron p and the magnetic flux ψ. We suppose that the magnetic field is dominated by a constant component along the z-direction. The time evolution of the three fields can be described by:

$$\partial_t \nabla_\perp^2 \phi + \left[\phi, \nabla_\perp^2 \phi\right] = \left[\psi, \nabla_\perp^2 \psi\right] - \kappa_1 \partial_y p + \nu \nabla_\perp^4 \phi, \quad (1)$$

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

$$\partial_t \psi + [\phi - p, \psi] = -v_\star \partial_y \psi + \eta \nabla_\perp^2 \psi, \quad (3)$$

where $v_\star = \frac{2\Omega_i \tau_A L_p}{\beta L_\perp}$. The sum of the electron and ion momentum balance equations leads to the plasma motion equation Eq. (1) where ν is the viscosity. Eq. (2) comes from the energy conservation and $\chi_\perp$ is the diffusivity. Then Eq. (3) is the Ohm's law with η the resistivity. $\beta = \frac{p_0}{B^2/2\mu_0}$ is the ratio between pressure and magnetic energies, L_p is the pressure gradient length, $L_\perp$ is a macroscopic length related to the island width, R_0 is the major plasma radius, $\Omega_i = \frac{eB}{m_i}$ is the ion cyclotronic frequency and τ_a is the Alvèn time. Equations (1), (2), (3) are normalized using the characteristic Alfvèn speed $v_A = B_0/\mu_0 n m_i = L_\perp/\tau_a$. On one hand, interchange instability is controlled by the κ_i parameters, $\kappa_1 = 2\Omega_i \tau_A \frac{L_\perp}{R_0}$ and $\kappa_2 = \frac{10 L_p}{3R_0}$ being linked respectively to the curvature and the pressure gradient. On the other hand, the nature of the tearing mode is controlled by the parameter $C = \frac{5T_e}{3L_\perp^2 \Omega_i^2 m_i}$. This coupling parameter enhances the thermic response when the current is teared and can indirectly weaken the response of the flow. The nature

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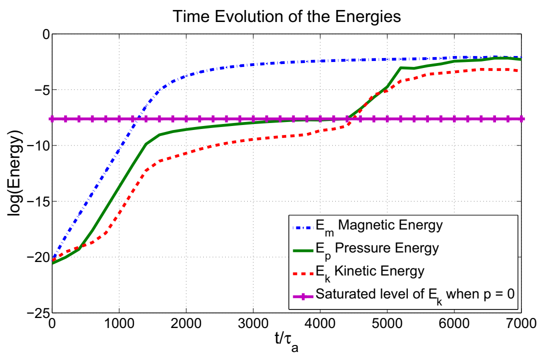

Fig. 1 Time evolution of the energies. The saturated level of E_k when $p = 0$ corresponds to a simulation of a classical tearing mode with $\Delta' = 6$.

of the linear and nonlinear dynamics of the magnetic island depends strongly of the intensity of the coupling. This model takes into account both tearing modes and electromagnetic interchange for the limit case where the electronic temperature is constant and the ion are cold. Moreover, the parallel ion dynamic is not included in the energy balance equation Eq. (2).

3. Nonlinear dynamics of the magnetic island

To characterize how small scale turbulence affects the evolution of a magnetic island, nonlinear numerical simulations using semi spectral codes are performed. The grid number is $n_x = 128$ for the radial direction and $n_y = 96$ for the poloidal direction. The box sizes are the same in the two directions : $L_x = L_y = 2\pi$. For simplicity, a focus on the interaction of basic mechanisms is done. In particular, the linear diamagnetic effect is suppressed, some interchange modes are unstable ($\kappa_1 = 10^{-2}$, $\kappa_2 = 0$) and a strong coupling between the pressure and the magnetic flux is chosen ($C = 1$). The shape of the equilibrium magnetic field is chosen to allow a tearing instability to develop with a poloidal mode number $k_y = 1$ with $\Delta' = 6$. Figure (1) shows the time evolution of the magnetic, pressure and kinetic energies for the case where $\nu = \chi_\perp = \eta = 10^{-4}$. Four regimes are observed. First, a linear regime where the magnetic island is formed. Second, the system reaches a quasi-plateau phase characterized by a slow growth of the energies. Then, the interchange unstable modes growth and a bifurcation occurs. Finally, the system reaches a new kind of dynamics.

During the two first regimes, we observe that, from an energetic point of view, magnetic flux and pressure both dominate, the kinetic energy being too weak to let the flow stabilizes the island. Owing to the high value of the coupling parameter, the linear

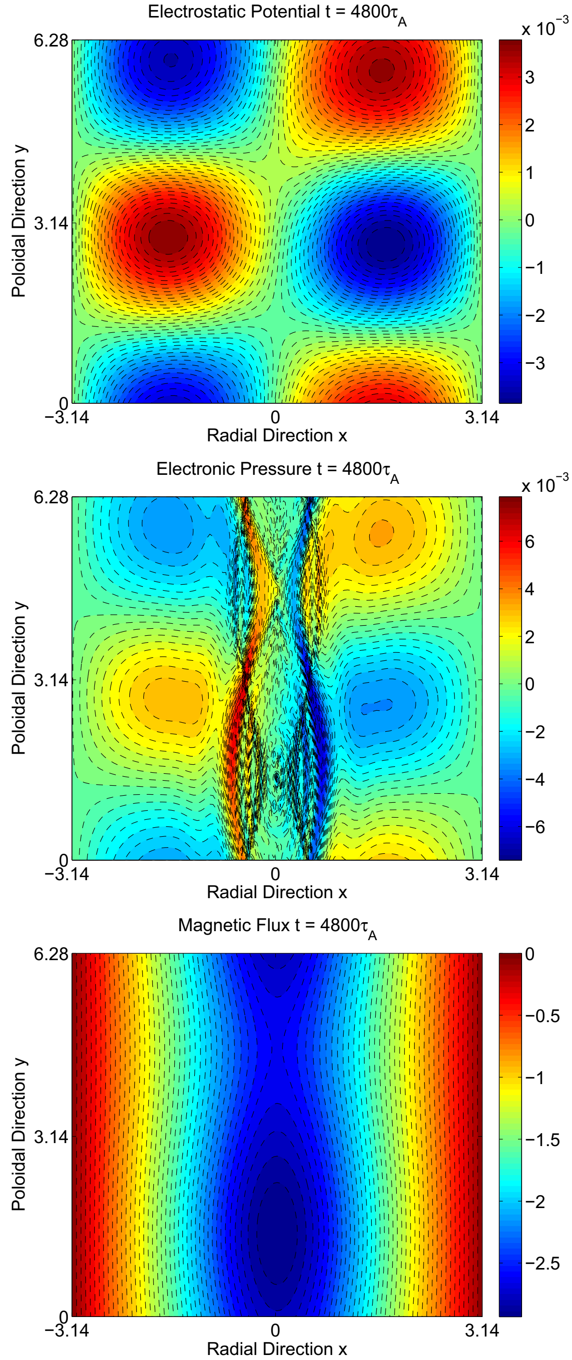

Fig. 2 Snapshot of the fields before the bifuration

and nonlinear growths of the magnetic island are controlled by an interplay between the pressure and the magnetic flux. Indeed, the magnetic island is maintained by pressure cells located in the vicinity of the separatrices. Moreover, these pressure cells generate a poloidal motion of the island and second compress the current sheath. In these two regimes, the electrostatic potential does not play any fundamental role in the dynamics. However, during the second phase, a part of the kinetic energy is not dissipated into the magnetic island and piles up outside. As a result, the kinetic energy increases

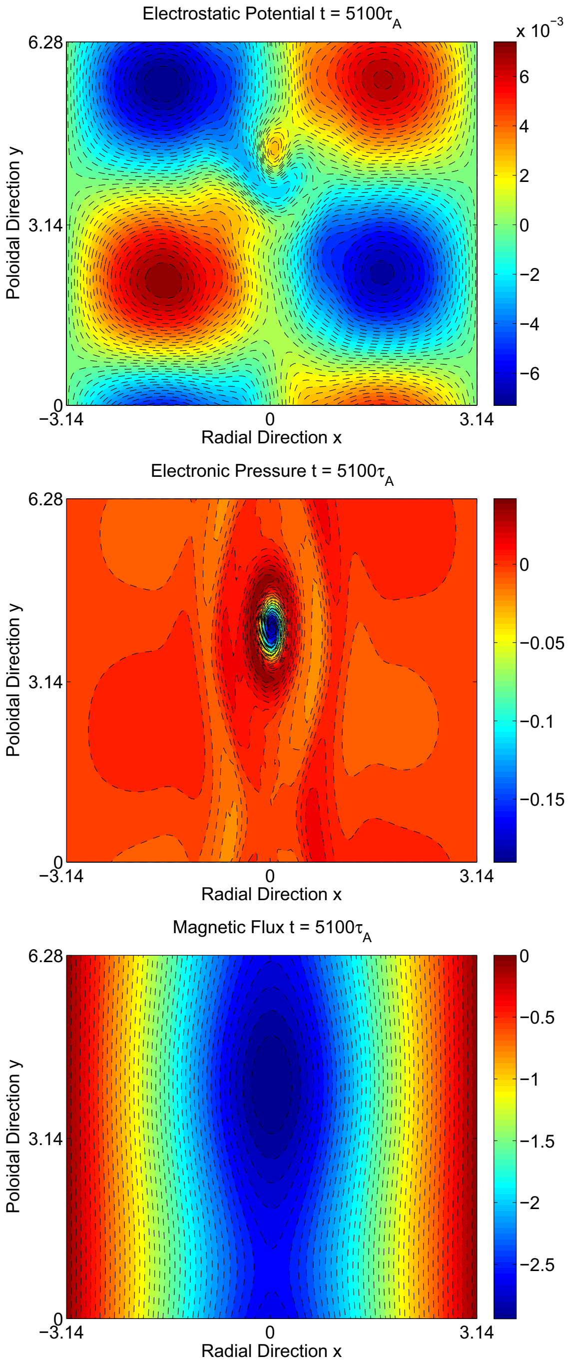

Fig. 3 Snapshot of the fields after the bifuration

gradually.

Far from the island, the current is not significant and the flow is fed mainly by two mechanisms: the incomming flow generated into the island and the electrostatic interchange process. Initially, the latter is energetically the weakest. At the end of the second regime, the flow has enough energy to let a coherent large scale interchange process to occur. Indeed, on the figure (2), snapshots of the electrostatic potential ϕ, the pressure p and the magnetic flux ψ, during the third regime, are presented. Outside the magnetic

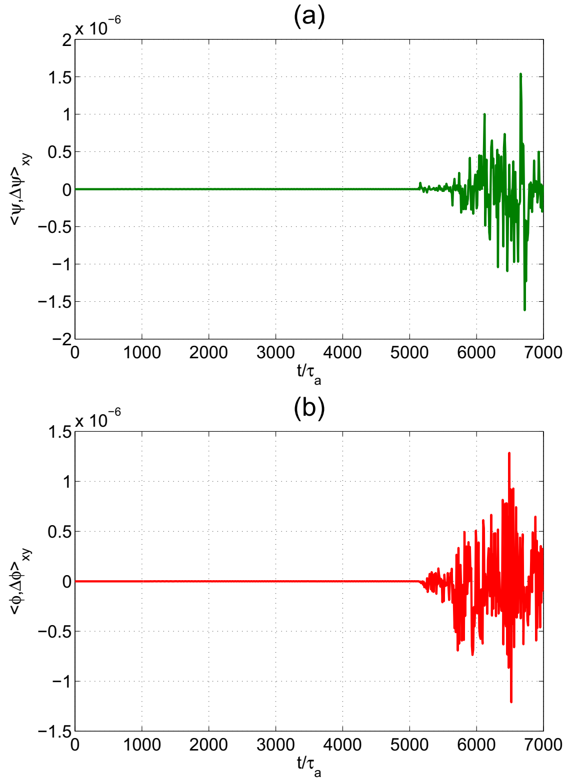

Fig. 4 Time evolutions of the Maxwell stress (a) and the Reynolds stress (b)

island, the pressure and the flow balance mutually: interchange cells are generated and are growing. However, the magnetic island is still maintained by pressure cells in the vicinity of the separatrices. We can also observe that, on the pressure snapshot, the interchange structure (outside the island) is in competition with the tearing structure (inside the island). This competition leads to a strong generation of small scales which, back, participate at the dynamics.

Finally the two structures are not compatible and a transition occurs. This is around $t \sim 5100\tau_A$ in the figure (1) where an abrupt growth of the kinetic and pressure energies is observed. The dynamical system finally adopts a new behaviour. On figure (3) snapshots of ϕ, p and ψ at $t = 5100\tau_A$ are presented. It shows that the competition between interchange and tearing structures leads to a drastic change of the presure topology. In fact, after the bifurcation, a pressure island appears inside de the magnetic island. Let us precise that whereas the magnetic island is a quasi linear structure mainly linked to the mode $k_y = 1$, the pressure island is a fully nonlinear structure characterized by an increase of many modes energie ($k_y < 8$) after the bifurcation.

On figure (4), time evolutions of the Maxwell stress (a) and the Reynolds stress (b) are presented. A

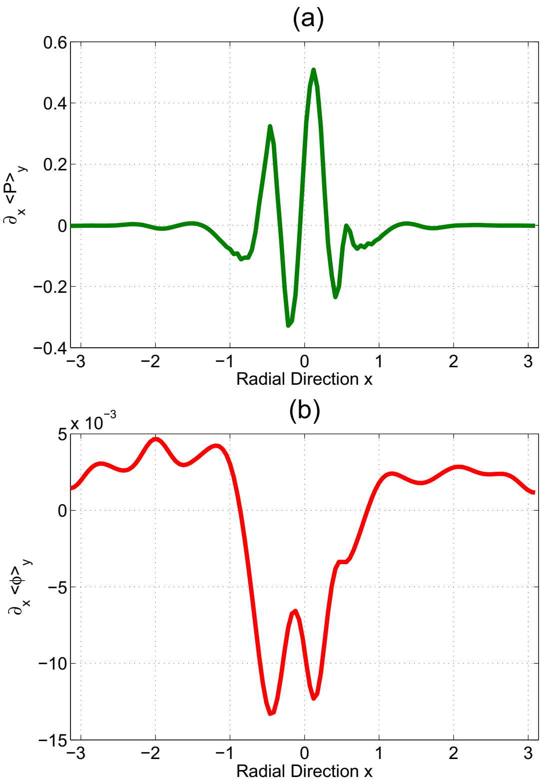

Fig. 5 Diamagnetic velocity (a) and zonal flow (b) versus radial direction at $t = 5500\tau_A$

strong increase of these stresses after the bifurcation is observed. It affects the nonlinear poloidal rotation of the magnetic island. Actually, from the beginning of the nonlinear regime ($t = 2000\tau_A$), a poloidal acceleration of the magnetic island is observed. Moreover, at the bifurcation ($t = 5100\tau_A$), a strong increase of the velocity and a change of direction of the rotation occur. In fact, the poloidal rotation is strongly affected by the competition between the tearing and interchange structures. The Ohm's Law (Eq.3) gives some insights into the origin of this island poloidal rotation. Indeed, as a first approximation, we can summarize the sources of the poloidal motion of the island (see Eq. 3) to the action of both the self-generated zonal flow, $v_{zon} = \frac{\partial}{\partial x} < \phi >_y$, and self-generated diamagnetic flow, $v_{dia} = \frac{\partial}{\partial x} < p >_y$ (brackets mean an average over the poloidal direction). In order to understand more precisely the role of these flows in the island rotation, diamagnetic velocity (a) and zonal flow (b) versus radial direction at $t = 5500\tau_A$ are presented on the figure (5). We can note that in terms of amplitude the diamagnetic velocity is largely higher than the zonal flow and thus it governs the nonlinear island poloidal rotation.

4. Conclusion

In conclusion, we have found regimes, characterized by a strong coupling between the pressure and the magnetic flux, where interchange mechanisms can affect strongly the dynamics of the magnetic island. In this case, the nature of the formation of the magnetic island is governed by pressure effects: the magnetic island is driven by the interplay between the pressure and the magnetic flux. Nonlinearly, there is a competition between interchange and tearing structures. As a result, small scales are strongly generated and a bifurcation occurs. Finally the system reaches a new dynamics characterized by a concentration of the pressure inside the magnetic island. Moreover, a poloidal rotation of the island is nonlinearly produced and is mainly driven by diamagnetic effects.

[1] K. Tanaka *et al.*, Nucl. Fusion **46**, 110 (2005)
[2] S. Takaji *et al.*, Nucl. Fusion **42**, 634 (2002)
[3] F. Militello, F. L. Waelbroeck, R. Fitzpatrick and W. Horton, Phys. Plasmas **15**, 050701 (2008)
[4] C. J. McDevitt and P. H. Diamond, Phys. Plasmas **13**, 032302 (2006)
[5] A. Furuya, S.-I. Itoh and M. Yagi, J. Phys. Soc. Japan **70**, 407 (2001)
[6] P. K. Kaw, E. J. Valeo and P. H. Rutherford, Phys. Rev. Lett. **43**, 1398 (1979)
[7] A. Sen and A. K. Sundaram, Phys. Fluids **24**, 1303 (1981)
[8] R. D. Hazeltine, M. Kotschenreuther and P. J. Morrison, Phys. of Fluids **28**, 2466 (1985)