Double tearing global reconnection dynamics in presence of a shear flow

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In tokamaks, the internal transport barrier is observed in reversed magnetic shear configurations where two low-order rational surfaces exist [1]. In such configurations, toroidal and poloidal flows, as well as temperature and density gradients can coexist close to the plasma core [2]. Note that such gradient can originate different resistive instabilities which are currently observed [3]. In fact, there is evidence that zonal flows exist and that the shear flow is localized in between resonant surfaces where the double tearing mode (DTM) can grow. The observed maxima of the flow velocity are weak compared with the Alfvén velocity v_A. Nevertheless, such flows can be important with respect to the turbulence level because the associated radial electric field can be linked to the formation of an ITB [4]. In fact, such configurations, allowing eventually the generation of a strong internal barrier, are part of the ITER scenarios for advanced confinement [5]. Previous works have investigated the influence of a Bickley jet on a tearing instability [6, 7] and on a DTM [8]. More recently, Bierwage *et al*. [9] have studied the influence of the core rotation amplitude - for a given sheared flow profile - on the stability of magnetohydrodynamic (MHD) and Kelvin-Helmholtz instabilities (KHI). These studies are mainly linear and a cylindrical geometry is used. They have shown that KHI can develop at large poloidal mode numbers and are strongly enhanced when the core rotation passes a critical value of the order of $10^{-2}v_A$ in the case where the distance between the resonant surfaces is small. They also found that below this critical value the growth rates of both the MHD and KH mode decrease with the amplitude of the core velocity. Recentely, Ishii *et al*. [10] have studied the different growth phases of weakly coupled non linear DTM with KHI stable rotation profile. Additionally, it as been shown in [11] that micro instabilities can play a crucial role on DTM dynamics.

In this work, we focus on the case where the shear flow is in between the two tearing instabilities. We find that poloidal flow delays the global magnetic reconnection process but does not inhibit it. We address the question of the origin of this delayed reconnection.

We use a two field model corresponding to a reduced (MHD) description of the plasma that provides a minimal framework to study the impact of a poloidal shear flow on a DTM. It consists of a set of two coupled equations for the fluctuations of the electrostatic potential ϕ and the magnetic flux ψ

$$\partial_t \omega + [\phi + \phi_0, \omega + \omega_0] = [\psi + \psi_0, j + j_0] + \nu \nabla_\perp^2 \omega \,, \quad (1)$$

$$\partial_t \psi + [\phi + \phi_0, \psi + \psi_0] = \eta j \,, \quad (2)$$

The poloidal equilibrium magnetic field is given by $\mathbf{B_0}(x) = \psi_0'(x)\mathbf{y}$ and the corresponding parallel current is therefore $j_0 = \psi_0''(x)$. $B_0 \sim \tanh((x \pm xr)/a_b)$ in the vicinity of the resonant surfaces $x = \pm x_r$ with $a_b = 0.5$. The equilibrium velocity and vorticity are given respectively by $\mathbf{v_0}(x) = \phi_0'(x)\mathbf{y} = A_v \tanh(x/a_v)$ and $\omega_0 = \phi_0''(x)$. Fig. 1 represents the two B_0 profiles (dashed line) and the v_0 profiles (full line) used in this paper.

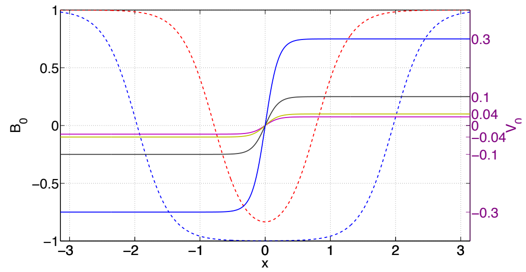

Figure 1: Equilibrium profiles of B_0 and V_0: The distances between the resonant surfaces are $\delta_{xs} = \pi/2$ (Red) and $\delta_{xs} = 5\pi/4$ (Blue).

Box sizes are $L_y = 2\pi$ (poloidal direction) and $L_x \geq 2\pi$ (radial direction). The radial size is modified according to the profiles to avoid wall effects. Viscosity is $\nu = 10^{-6}$. The $m = 1$ DTM is unstable in all cases. But the nature of the dominant instability depends on the level of the resistivity. Fig. 2 represent the growth rate of the $m = 1$ mode as a function of resistivity for the case where the distance between the resonant surface is $\delta_{xs} = \pi/2$. Without shear flow (dashed blue line), as expected, the growth rate of the mode $m = 1$ increases with resistivity. Note that no clear power law is followed because $\delta_{xs} \not\ll 1$ [$L_\perp$]. Introducing a weak shear flow (red curve (2)), *i.e.* $A_v = 0.03$, at high resistivity ($\eta \geq \eta_c \sim 2.10^{-5}$), the shear flow tends to reduce the linear growth rate. At low resistivity ($\eta \leq \eta_c$) the growth rate is enhanced. In fact, the system presents 4 regimes according to the level of the resistivity. At high resistivity, the $m = 1$ linear growth rate is roughly the same with or without shear flow. in this case, the shear flow does not weaken the interaction between the resonant surfaces where DTM is growing. When resistivity decreases, a new regime appears in which DTM is still dominating the dynamics, but magnetic islands are rotating. This might be expected even for lower island rotation velocities than $A_V = 0.03$ In the range $\eta = [2.10^{-5}, 5.10^{-4}]$, the magnetic field does not stabilizing anymore KHI in the shear layer. (This would not be the case in the limit $a_v \to 0$ [12]). Typically within these parameter range, KHI is unstable for modes $m \leq 5$. Finally, below $\eta = 2.10^{-5}$, KH unstable $m = 1$ mode dominates the DTM.

Figure (3) shows the linear velocity of magnetic islands as a function of equilibrium velocity amplitude for $\nu = 10^{-4}$, $\eta = 10^{-3}$ and $\delta_{xs} = 5\pi/4$ (dashed blue curve in Fig. 1). The latter parameter values allow a clear space separation between the resistive and the shear layers. Dashed lines would correspond to the limit of islands flowing at the imposed velocity A_v. It is found that there exists a critical amplitude A_{vc} above which islands rotate in opposite directions, roughly, at velocity $v_{\text{island}} \sim A_v - A_{vc}$ where $A_{vc} \sim 0.035[v_A]$: The momentum injected through the shear flow tends to generate vortices in the shear layer which tilt the DTM flow structure before destabilizing it at $A_v = A_{vc}$. The supplementary injected momentum is not compensated by any other magnetic mechanism in mean and brings free energy for island rotation. The de-correlation of the two tearing structures weakens the resulting growth rate.

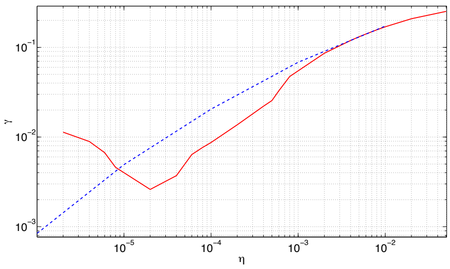

Figure 2: Growth rate of $m = 1$ mode, as a function of resistivity.

Contrary to the case without shear flow, there is quasilinear generation of a mean flow because of the island rotation or even the tilting of the $m = 1$ flow. The nonlinear dynamics in all cases presents three phases, first a nonlinear saturation of the magnetic energy corresponding to saturation of the $m = 1$ magnetic structures at the resonant surfaces. Second, island rotation stop and the island extends radially towards the other resonant surface. Third a global reconnection occurs which means that the mean poloidal magnetic fields does not have anymore resonant surface. The second phase is occurring in Fig. 4. Just before the global reconnection, total electrostatic potential (Fig. 4 b) presents a huge elongated vortex corresponding mainly to a combination of the modes $m = 0$ and $m = 1$. These modes both, counter act the imposed flow in between the resonances, and by modifying the elongation direction allow the radial extension of the magnetic island.

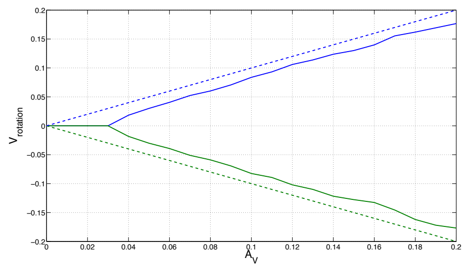

Figure 3: Linear velocity of magnetic island (full lines) and value of equilibrium velocity (dashed lines)

In this work, we have shown that shear flow have a strong influence on DTM dynamics. The coexistence of the two instabilities gives 4 different linear regimes. We have shown the existence of a critical amplitude of the impose plasma flow above which plasma rotates. In presence of a shear flow, the mechanisms at play (tilting, $m = 0$ flow generation, KH instability, DTM) delays the time at which global reconnection occurs. However, precise quantification requires investigation of the impact of the numerous parameters involve in the system. For instance, viscosity should play an important role in the shear layer.

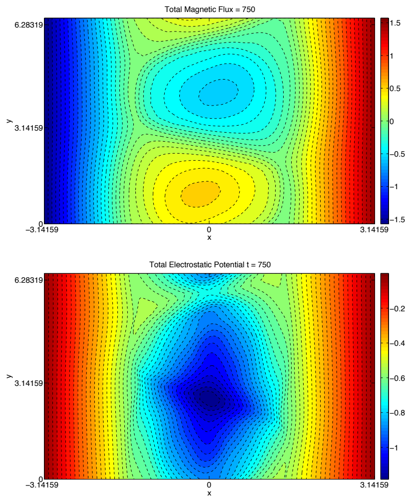

Figure 4: Total magnetic flux and electrostatic potential just before global reconnection.

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