*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-2.072 (2008)*

Nonlinear double tearing evolution with Kelvin Helmholtz instability

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We investigate the dynamics of a double tearing mode in presence of a shear flow. In fusion devices, the double tearing mode can exist whenever the plasma has two rational surfaces. In such reversed magnetic shear plasma situations, internal transport barrier can be observed [1]. Toroidal and poloidal flow, as well as temperature and density gradient, coexist close to the core of plasma [2] and generally appear in between the two resonnant surfaces. Such configurations, allowing eventually the generation of a strong internal barrier, are part of the ITER scenarii for advanced confinement [3]. In this work, we focus on the case where the shear flow is in between the two tearing instabilities, within the framework of magnetohydrodynamics, using a 2D slab geometry. It means we only focus on the mechanisms underlying the interaction of a poloidal flow with a reconnecting magnetic field. It is well-known that a constant magnetic field stabilizes a shear flow instability when the initial flow is vortex sheet [4], as far as the Alfvén velocity exceeds the amplitude of the vortex sheet. Less singular profiles have been studied and, in particular, it has been investigated the influence of a Bickley jet on a tearing instability [5,6] and on a double tearing instability [7].

$$\mathbf{B}_{\mathrm{CS}}(x) = A_b \tanh(x/a_b)\mathbf{y} \tag{1}$$

Eq: 1 is a standard profile for resistive current sheets. Here, by convention, x corresponds to the radial position and y the poloidal one. Ofman has shown numerically that when the flow is forced with a velocity field $\mathbf{V}(x) = A(1/\cosh(x/a)-1)\mathbf{y}$, Kelvin-Helmoltz (KH) instability coexist with the single tearing one when $a < 1$. He also studied the double tearing instability in presence of a shear flow profile,

$$\mathbf{V}_0(x) = A_v \tanh(x/a_v)\mathbf{y} \tag{2}$$

in cases not subject to KH instability. In this work, using similar profiles we will see that KH can be present even when the amplitude of the flow is small and we present some nonlinear results.

We use a 2D slab collisional magnetohydrodynamic model with two fields

$$\begin{aligned} \partial_t \psi &= [\psi,\phi] + \eta J \,, \\ \partial_t \omega + [\phi,\omega] &= [\psi,J] + \nu \nabla_\perp^2 \omega \,, \end{aligned} \tag{3}$$

where $[A,B] = \partial_x A \partial_y B - \partial_x B \partial_y A$ is the Poisson Braket, ϕ the eletrostatic potential, ψ the magnetic flux, $\omega = \nabla^2\phi$ the vorticity and $\mathbf{J} = \nabla^2\psi$ the courant. In this set of equations unit time is τ_A the Alfvèn time.

The equilibrium profiles are $V_0(x)$ (Eq. 2) for the shear flow and we take an symmetric profile for the magnetic field such that $B_0(x) = \mathbf{B}_{CS}(x + LX/4)$ if $x > LX/2$, up to some modifications to ensure continuity of the profile and its derivatives. The box sizes are $LX = LY = 2\pi$, the viscosity is $\nu = 10^{-4}$, the resistivity $\eta = 10^{-3}$, $A_b = 0.92$ and finally $a_b = 0.5$. Equilibrium velocity profile V_0 is therefore exactly located in between the two current sheets and we fix its gradient length $a_v = 0.2 < 1$. With this set of parameters, the area where B_0 and V_0 have pronounced gradients do not overlap.

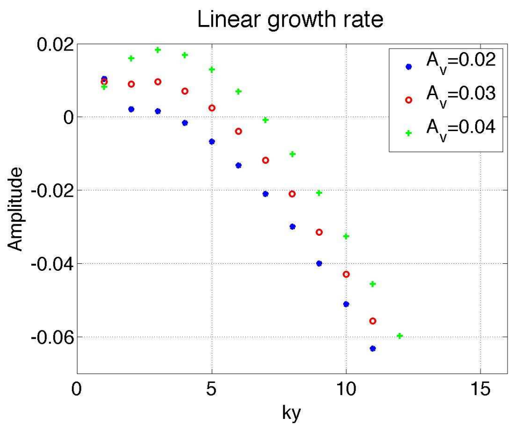

Figure 1: Linear growth rate for different amplitudes of the shear flow.

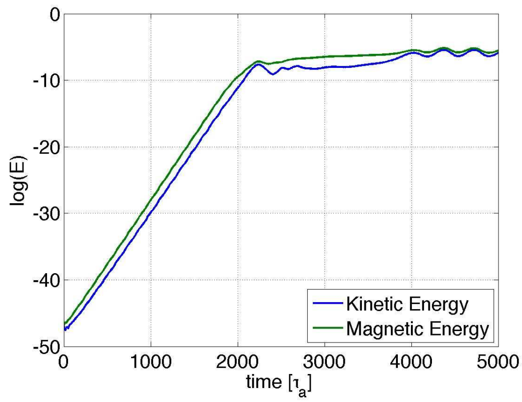

Figure 2: E_k [blue] and E_m [green] versus time.

In Fig. 1 , we plot the linear growth rates of the instabilities as a function of the poloidal mode number k_y for various flow amplitudes $A_v = \{0.02, 0.03, 0.04\}$. We clearly observe that a KH instability is present and has a maximum growth rate at $k_y = 3$ in the last two cases. The magnetic double tearing instability occurs only at $k_y = 1$, as expected ($\Delta' = 6$). There is a strong dependence on the growth rate of the KH with A_v, which is present because $a_v < 1$, even though $A_v/A_b \ll 1$. In the first case, magnetic instabilities dominates and the convers occurs in the last one. An interesting situation is when $A_v = 0.03$, both kind of instabilities having close maximum growth rates may strongly interact nonlinearly.

In Fig. 2, we plot the kinetic E_k and magnetic E_m energies as a function of time. Linear growth of the instabilities occurs until $t \sim 2000\tau_A$. A snapshot of the flux ψ and the potential ϕ are shown in Fig 3 at $t = 3000\tau_A$, showing both the two magnetic islands and the KH structures in between. We also show in Fig. 4, the poloidal position of the two magnetic island. Initially they rotate in opposite diretions as prescribed by the equilibrium flow $V_0(x)$ at the velocity A_v, then nonlinearly they both stop their rotation and finally rotate again but in the same direction to a velocity close to A_v. This last phase corresponds to the oscillating phase, in an energetic point of view (see Fig. 2) and exhibits a complicate behavior. In particular, the Kelvin-Helmholtz vorticies shape is modified. Indeed the alternated bipolar signed structures becomes monopoles. Let us also mention that the width of the islands oscillates in opposition of phase in this asymptotic regime.

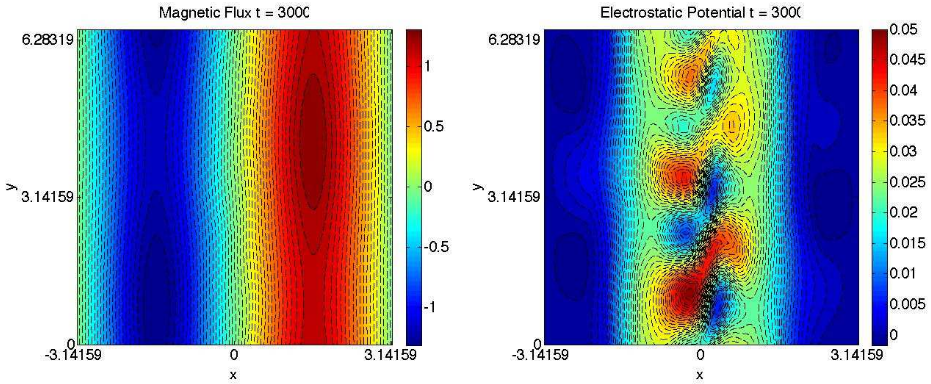

Figure 3: Electrostatic potential and magnetic flux at $t = 3000\tau_a$.

In this work, we have shown that even when a weak shear flow is present, it can present a KH instability in a double tearing configuration. This kind of configuration can lead to a inversion of direction of a rotation of a island, both finally rotating in phase. More investigation is of course needed. For instance, how does the viscosity and the distance between the island influence the dynamics?

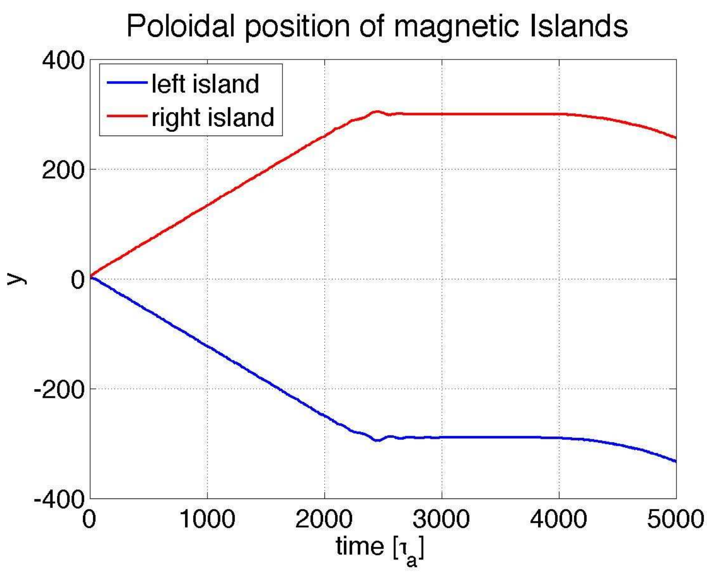

Figure 4: Position of islands versus time.

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