§7. Full Magnetohydrodynamic Simulations of Interchange Mode with Diamagnetic Effects and Dissipation

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i) Introduction In the recent decades, there has been a strong emphasis on the non-linear studies of magnetohydrodynamic (MHD) modes, both in the tokamak and stellarator communities, allowed by the constant improvement of computing hardware and techniques. However this should not lead to the conclusion that everything is known about the linear stability of MHD modes. As a matter of fact, the stability of stellarator plasmas against interchange modes is not sufficiently understood. In particular, the largest value of the volume average $\langle\beta\rangle = 5\%$ (β is the ratio between kinetic and magnetic pressure) has been obtained without major MHD event in the Large Helical Device (LHD) [1]. The rotation of the mode, which is related to the stability through the phenomenon of mode locking [2], is also poorly understood. Whereas the theory predicts rotation in the direction of the ion diamagnetic drift or very small rotation, the plasma is observed to rotate in the electron direction [3].

ii) Methods and objectives The present study sums up the results obtained using the MIPS code [5]. The code is an initial value MHD stability code including resistivity, viscosity, perpendicular heat and density diffusivity as well as ion diamagnetic effects (also sometimes referred to as ion gyroviscous effects). The code uses the equilibrium provided by the HINT2 code [6] as an input. We are interested in the effect of dissipation on diamagnetic stabilization of ideally unstable modes. The stabilization of the ideal mode by ion diamagnetic effects obeys to the rule

$$\Omega(\Omega - \omega_i^\star) = -\gamma_I^2,$$

where $\Omega = \omega + i\gamma$ is the mode's complex frequency and γ_I is the ideal growth rate. The question is whether this stays approximately true when there is some dissipation, in other words, can we replace the above equation with the test dispersion relation

$$\Omega(\Omega - \omega_i^\star) = \Omega_D^2, \tag{1}$$

where $\Omega_D = \omega_D + i\gamma_D$, which can be complex, is the frequency of the mode including dissipation but no diamagnetic effects.

iii) Results We have found two regimes for the validity of *eq.* (1), depending on the strength of the dissipation, measured by the ratio γ_D/γ_I. The results [4] are summarized on Figure 1.

For $\beta = 2\%$, the dissipation is quite weak, γ_D and γ_I are of the same order of magnitude ($\gamma_D/\gamma_I = 0.6$), and *eq.* (1) is reasonably recovered. As a result, we observe the stabilization of the growth rate (blue solid line) and the frequency (solid red line) proportional to $\sim 0.3\omega_i^\star$, close to the prediction of $\omega = 0.5\omega_i^\star$.

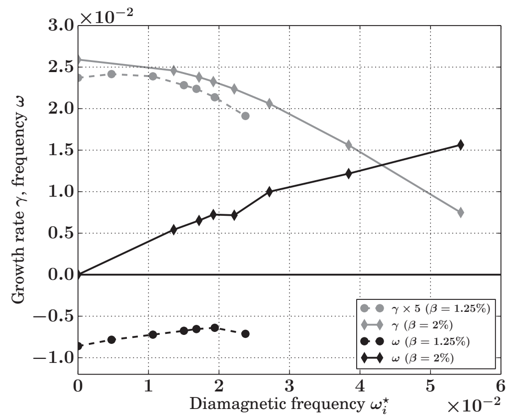

Fig. 1: Growth rate and frequency of the interchange mode with respect to the diamagnetic frequency in a large beta (weak effect of dissipation) case and a low beta (strong effect of dissipation) case.

For $\beta = 1.25\%$, the ideal growth rate is smaller and the dissipation has a much larger influence, so that $\gamma_D/\gamma_I = 0.2$. In this case, the behaviour of the mode complex frequency is completely different from *eq.* (1). For small values of $\omega_i^\star$, we observe some destabilization (blue dashed curve, the growth rate has been multiplied by 5 for visibility), then stabilization for $\omega_i^\star > 10^{-2}$. This stabilization is much smaller than expected by *eq.* (1). Indeed it predicts a much faster stabilization than in the first case because γ_D is roughly 5 times smaller. The rotation (red dashed curve) is also very different. One should notice that the rotation is in the electron direction and does not vanish for $\omega_i^\star = 0$. This means that $\omega_D \neq 0$. In fact we have been able to show that this is due to the perpendicular heat diffusivity, which causes a bifurcation of the growth rate and frequency. This is the reason for the modification of the behaviour with respect to the ion diamagnetic effect. This bifurcation is the topic of the second part of this report.

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3) Y. Takemura, *et al.* Plasma and Fusion Research **8(0)**, 1402123 (2013).

4) T. Nicolas, *et al.* Plasma and Fusion Research (2015).

5) Y. Todo, *et al.* Plasma and Fusion Research **5**, S2062 (2010).

6) Y. Suzuki, *et al.* Nucl. Fusion **46(11)** (2006).

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