# §8. Bifurcation of the Growth Rate and Frequency of the Interchange Mode with Diamagnetic Effects and Perpendicular Heat Conductivity

Nicolas, T., Ichiguchi, K.

**i) Introduction** Here we report for the first time a bifurcation of the growth rate of the ideally unstable interchange mode, which is due to the perpendicular heat diffusivity. This phenomenon has a large influence on the rotation and the diamagnetic stabilization. This explains the results obtained with the MIPS code on the ideally unstable modes, detailed in the first part.

We also present the result that the rotation is in the electron direction for ideally stable modes triggered by resistivity, when perpendicular heat diffusivity and viscosity are included in the MHD equations.

**ii) Methods** The MHD stability is studied with a 3-field model derived from Strauss equations in cylindrical geometry $^{1)}$. In addition, the model includes resistivity $\eta$, viscosity $\nu$, perpendicular heat conductivity $\chi_\perp$ and both electron and ion diamagnetic effects (the ion diamagnetic effect is sometimes also referred to as the ion gyroviscous effect). The model contains several eigenmodes for a given mode helicity, and the code can give the evolution of their growth rate and frequency with the physical parameters.

**iii) Ideally unstable modes** When all dissipation parameters $\eta$, $\nu$, $\chi_\perp$ and the diamagnetic effects are set to zero, the model is that of ideal MHD. In ideal MHD the mode is purely growing/damped or purely rotating. The hermiticity is not preserved when dissipation is switched on. Increasing $\chi_\perp$ causes the growth rate of the most unstable eigenmode to decrease, as one would expect, but the one of the second largest eigenmode increases. When $\chi_\perp$ is equal to a critical value $\chi_c$, the growth rates of these two modes become equal and stay equal for $\chi_\perp > \chi_c$. At $\chi_\perp = \chi_c$, the real frequency of the mode, which was initially zero, exhibits a bifurcation. The two eigenmodes then have same growth rate but equal and opposite frequency. One rotates in the ion direction, the other in the electron direction. The situation is summed up in Figure 1. The existence of the bifurcation can be understood analytically by using the asymptotic matching method of reference $^{2)}$.

The presence of the bifurcation completely modifies the diamagnetic stabilization. We note $\omega_i^\star$ the ion diamagnetic frequency. When $\chi_\perp > \chi_c$, there is a degeneracy of the growth rates for $\omega_i^\star = 0$. In this case, the mode has no preferential direction of rotation. The degeneracy is removed when $\omega_i^\star \neq 0$. In general, one of the two modes will be destabilized instead of being stabilized. Which one of the two mode becomes dominant is determined by the viscosity. For large values of the viscosity, the dominant mode rotates in the electron direction, which could be consistent with the result that the modes rotate in the electron direction in the experiment.

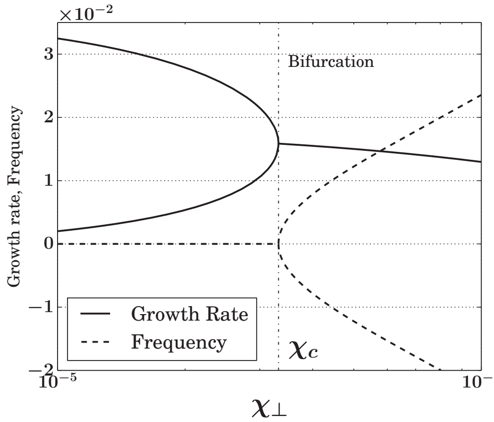

Fig. 1: Frequency and growth rate of the first two most unstable modes

The qualitative results of the 3 field model are all recovered in full MHD simulations making use of the MIPS code $^{3)}$. Thus this is a robust phenomenon. In a further study, we plan to study the case of a realistic equilibrium in order to see if this phenomenon really occurs for realistic values of the parameters.

**iv) Ideally stable modes** Modes that are ideally stable can be destabilized by a finite value of the resistivity. In this regime the scaling of the mode growth rate with resistivity is $\gamma \propto \eta^{1/3}$. The bifurcation described above does not apply to ideally stable modes.

The theoretical effect of the diamagnetic frequencies on the mode growth rate and frequency is also given in reference $^{2)}$, when no dissipation other than the resistivity is included. The result is that the electron and ion diamagnetic effects have a stabilizing influence (in the ideally unstable case, the electron effect is negligible), and that the frequency almost vanishes.

However, when dissipation is included, the mode starts to rotate in the electron direction. Both viscosity and perpendicular heat diffusivity independently cause rotation in the electron direction. When the stabilization by the dissipation becomes large, that is, when $\gamma_D \ll \gamma_R$, where $\gamma_R$ is the resistive growth rate and $\gamma_D$ the growth rate including $\eta$ and/or $\chi_\perp$, the value of the rotation approaches $\omega/\omega_e^\star = 1$.

1) H. Strauss. Plasma Physics **22(7)**, 733 (1980).

2) S. Gupta, *et al.* Phys. Plasmas **9(8)**, 3395 (2002).

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

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