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Plasma velocity and mode dynamics in the Single Helicity RFP configuration

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Introduction

The interaction between magneto-hydro-dynamic (MHD) modes and plasma fluid velocity is a very important issue in plasma physics. Examples are the linear stabilization induced by plasma rotation [1,2,3] or the wall-locking phenomenon of MHD modes and plasma braking [4,5] which often leads to plasma disruptions or to severe limitation of plasma performances. Most of the simulation work in this area have dealt with simplified models [4,6,7] which describe the resistive/viscous force balance on a magnetic island.

In this work the results obtained using a cylindrical nonlinear MHD code (DEBS) are discussed especially in relation to the frequently used "non-slip" condition [7], which states that the rotation frequency of the mode and the angular rotation velocity of the plasma are the same at the resonance surface of the mode, i.e.

$$\Delta\omega_{res} = (\omega_{plasma} - \omega_{mode}) = (\frac{m}{r_s}V_\theta + \frac{n}{R}V_z) - \omega_{mode} = 0 \qquad (1)$$

where ω_{mode} is the (m,n) mode phase velocity (m and n being respectively the poloidal and toroidal mode numbers) and V_θ, V_Z are the mean plasma velocities in poloidal and toroidal directions and R is the torus major radius. Eq.(1) should be evaluated at the radius r_S such that:

$$q(r_s) = \frac{m}{n}$$

As reference case we consider the so called "Single Helicity" (SH) state obtained in RFP simulations, in which one dominant mode is maintaining the plasma in a quasi stationary ohmic state [8,9]. This is an interesting and relatively simple case, where the nonlinear interactions of the dominant mode with the rest of the spectrum is particularly reduced if compared with the usual turbulent RFP state where many MHD modes are simultaneously excited with a comparable amplitude .

Numerical simulations with DEBS

DEBS is a 3D cylindrical pseudo-spectral code [10] using finite difference in radial direction and Fourier decomposition for the poloidal and toroidal angles. The plasma is treated as a viscous-resistive single fluid surrounded by either a resistive or an ideal wall. In the simulations presented here we consider an ideal wall. In order to induce in the plasma a relevant mean toroidal flow (up to 15% of the Alfvèn speed in these simulations) the z component of the momentum equation has been modified by adding a drag term, as described in [11]. As shown in [12] the SH state can be obtained below a critical Hartmann number. In this paper we consider a relatively low Lundquist number, i.e. S=3300. This has the advantage to limit the required numerical resolution ($n_r = 64$, $n_\theta = 10$, $n_z = 42$ have been used) and also to obtain the SH state for a relatively wide range of Prandtl numbers (P), i.e. the ratio between the viscous and the resistive dissipation scales. For the cases presented here P has been varied in the range 8 to 80. An example of the modes (different n's) radial energy (averaged over the plasma volume) is given in Fig.1 for the m=1 harmonics for P=80. The dominant helicity is the n=-10 mode which resonates approximately at r=0.4 (the minor plasma radius is used as normalization constant). The case shown in Fig.1 is also characterized by (after t=0.63) (times are normalized to the global resistive diffusion time) a steady state toroidal shear flow corresponding to an on axis toroidal velocity, $V_z(0)$, of about 0.1 of the Alfvèn speed and decreasing parabolically to zero toward the wall.

Results

A first observation is that during the phases of time variation of the plasma velocity (a fast, step-like time variation was applied) the "non-slip" condition is hardly verified (especially for low Prandtl number simulations). This is shown for example in Fig.2 where the phase velocities at 10 different radial positions is plotted versus time. It is seen that in the initial stage (this period is shorter at higher P) the phase velocity of the mode is not the same for all the radial positions and is generally different from the final steady state value, corresponding approximately to the "non-slip" condition. Note also that with an ideal wall the steady state (final) mode angular velocity is the same for all radii. In Fig. 3, the dominat mode(m=1,n=-10) volume averaged radial energy is shown versus the applied on axis toroidal velocity. It is observed that a decreasing of the the mode energy is obtained at high velocity, but also that this reduction depends on the Prandtl number, and is more consistent for the most dissipative case. Looking at the deviation from the “non-slip” condition (as given in Eq.(1)) the mode angular velocity is plotted in Fig.4 versus the plasma angular rotation at the resonance surface for P=8 and 80 cases. The “non-slip” condition is very well verified for both P values. Note that although only a toroidal velocity is induced in the plasma also a poloidal plasma velocity develops and both component should be taken into account to calculate the plasma angular rotation.

Discussion and conclusions

Using a 3D cylindrical code with ideal wall we have shown that for cases where the mode-mode interactions are weak, i.e. the so called Single Helicity RFP state, the mode respond to an increase of the plasma velocity by obeying to the so called “non-slip” condition [7].

This response seems not to depend on plasma viscosity at least for the Prandtl and Lunquist numbers consider in this paper. We point out that in our calculations the energy of the dominant mode is consistently determined by the plasma dynamical evolution. By varying P we have explored a range of island sizes from few percent (at high P) to 10% of the plasma minor radius (low P). Some deviation from the “non-slip” condition (see Fig.2) is observed in transient regimes during the phase of plasma acceleration and even for some time after that a steady state flow is already established in the plasma. This is an indication that some precaution should be used when the “non-slip” condition is used in dynamical codes.

This study will serve as a basis for future work where higher Lundquist numbers will be explored. Moreover we will extend the present work to cases where the nonlinear coupling between modes is more important, as in the standard RFP operation. In fact, preliminary results indicate that under these circumstances the dynamical behavior tends to be much more complicated.

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Fig.1

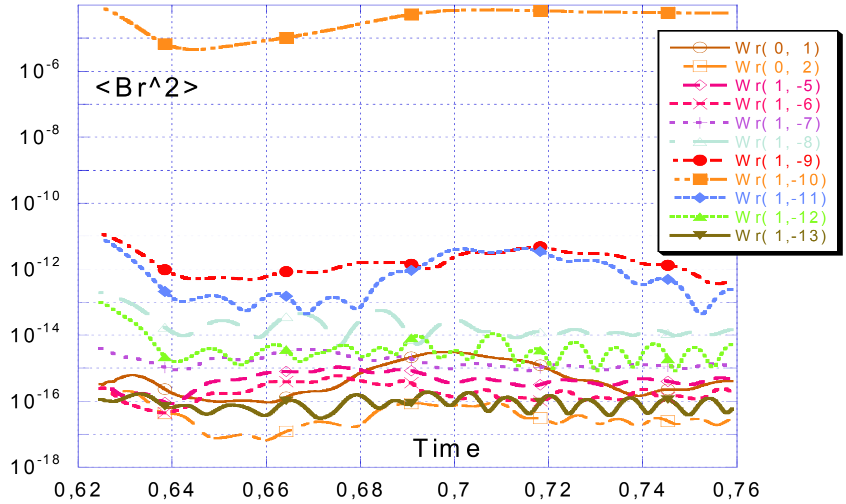

Fig.2

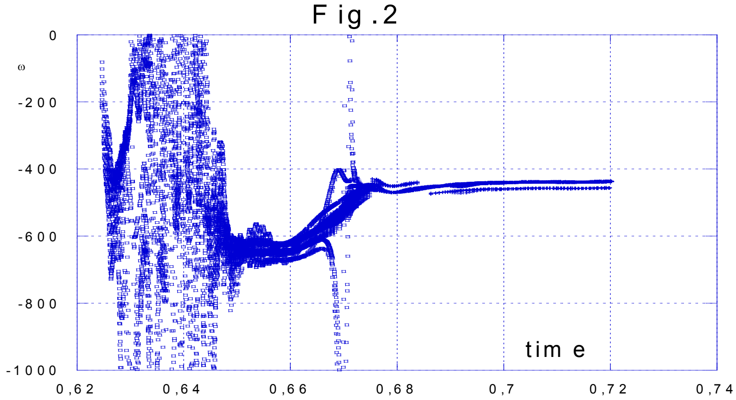

Fig.3

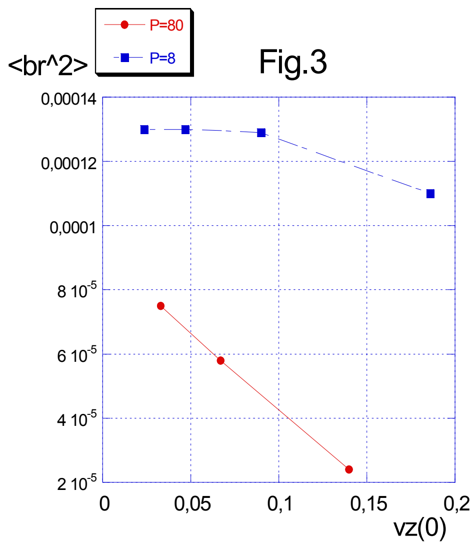

Fig.4