ON STABILISATION OF RESISTIVE PRESSURE DRIVEN MODES IN THE REVERSED-FIELD PINCH

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Abstract

Sheared fluid flow is shown to only weakly reduce fluctuations in the finite beta reversed-field pinch. This preliminary result is obtained from 3-D non-linear resistive MHD simulations including energy transport physics, using realistic plasma parameters.

1. Flow shear stabilisation of resistive modes

The role of sheared velocity flow on stability of linear and nonlinear plasma modes [1] was appreciated already at an early stage in fusion research [2]. The resistive tearing mode growth rate was soon found to be reduced by flow velocities of the order the resistive diffusion velocity even at moderately high wavenumbers [3,4,5].

Linear analysis does not provide the full picture, however. In the case of sheared axial flow, the linear mode structure is moving uniformly in the axial direction [6]. Thus the important effect of flow "tearing" of the instabilities is absent. To explore the role of sheared flow in the RFP, a fully nonlinear model has to be used. This is the main theme of the present work, although we have sought some tentative guidance in a linear analytic study of the m=0 mode.

Our first simulations show that m=0,1,2 RFP tearing modes are only somewhat reduced by either axial or poloidal sheared flows. It has been experimentally and computationally demonstrated, however, that a more suitable way to stabilise tearing modes in the RFP is through appropriate shaping of their driving source, the parallel current gradient. Once this is done, by whatever means, there remains the difficulty with resistive interchange (or g-) modes. These are driven by the pressure gradient and must be substantially stabilised, as compared to their linear growth rates, by flow or kinetic effects. We are presently addressing these topics, but will not discuss them further here.

2. Linear theory for m=0 resistive g-modes

The linearised resistive MHD equations can be used to estimate the effect of sheared poloidal flow. We assume finite pressure (adiabatic), incompressible m=0 perturbations in cylindrical geometry. By balancing the rate of change of parallel kinetic energy to the radial restoring power in the standard manner, the normalised resistive layer width becomes $d=(\gamma r^2/(k^2R^2B_\theta^2q'^2S))^{1/4}$, where the mode resonance is at radius r. Here γ denotes growth rate,

k is the axial wavenumber, R is the major radius, q the safety factor and S the Lundquist number. A prime denotes radial differentiation. Normalisation parameters are the plasma radius, the Alfvén velocity and the on-axis magnetic field.

After taking the curl of the momentum equation, dominating terms in S and k can be balanced to determine the growth rate. There results

$$\gamma = \left[\frac{2k(-p' - r^4(\rho u_\theta^2 / r^4)'}{r|B_z'|} \right]^{2/3} S^{-1/3} \quad . \tag{1}$$

For $u_\theta(r) = 0$, the growth rates obtained from (1) is in good agreement with those obtained from a code including the full, finite pressure resistive MHD model. Unless $u_\theta(r)$ increases strongly with radius, it is seen that poloidal flow destabilises resistive RFP modes in the linear regime. A physical explanation may be that unsaturated poloidal rotation adds like a centrifugal force component to the pressure force in the bad curvature RFP geometry. We further note that tearing modes, having the dependence $S^{-3/5}$, are singular in the sense that they convert to g-mode dependence $S^{-1/3}$ when flow is included.

A more decisive answer to the role of sheared flow must be given within the framework of nonlinear MHD. In the following we address this problem with a resistive plasma simulation code also for $m \neq 0$ modes, using both sheared poloidal and axial flows.

3. DEBSP nonlinear code

DEBSP is formulated using the nonlinear, three-dimensional resistive MHD equations in cylindrical geometry [7]. The spatial approximation employs finite differences in the radial coordinate, and the pseudo-spectral algorithm in the periodic poloidal and axial coordinates. A leapfrog algorithm is used to advance wave-like terms and advective terms are treated with a predictor-corrector method. Plasma transport is modelled by an energy equation including resistive heating, anisotropic heat conduction and convection.

An ad hoc drag term is introduced into the momentum equation to mimic the effect of (externally or internally imposed) plasma rotation:

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v} \cdot \nabla)\mathbf{v} - \alpha(\mathbf{v} - \mathbf{V}_0) + \frac{1}{\rho}\mathbf{j} \times \mathbf{B} - \frac{\beta_0}{2\rho}\nabla p + \frac{\nu}{\rho}\nabla^2 \mathbf{v} \quad . \tag{2}$$

Standard normalised notation is used, apart from that the resistive time τ_R is used for normalisation. The last term represents viscosity.

Both poloidal and axial flow profiles are introduced using the mean $((m,n)=(0,0))$ components of the velocity:

$$V_{0\theta}(r) = v_{\theta 0}\, r(1 - r^2)$$
$$V_{0z}(r) = v_{z0}(1 - r^2) \tag{3}$$

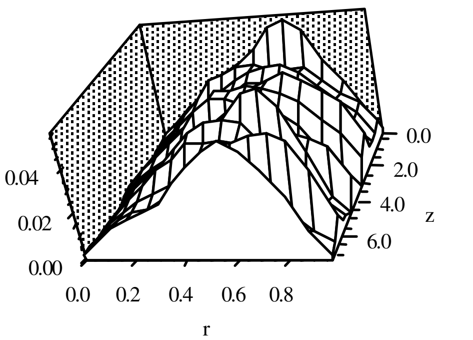
Our base run ($\mathbf{V}_0=0$) uses the input parameters a=0.2 m, the constant density $n_0=5.0 \cdot 10^{13}$ m^{-3}, a central temperature T_0=50 eV, and B_0=0.2 T. This corresponds to a poloidal beta value $\beta_{\theta 0}$ = 0.05, an on-axis Lundquist number $S_0=7.6 \cdot 10^4$ and a plasma current of 125 kA. A perfectly conducting wall is chosen, the aspect ratio is 1.25 and Θ=1.8. The grid resolution is given by 161 radial nodes, 64 axial modes and 16 poloidal modes (before dealiasing). At the end of the run (t=0.02τ_R) we find S=8.7·10^4, T=49 eV, and β_θ= 0.18. Field reversal occurs at r=0.82. The energy confinement time becomes τ_E = 105 μs.

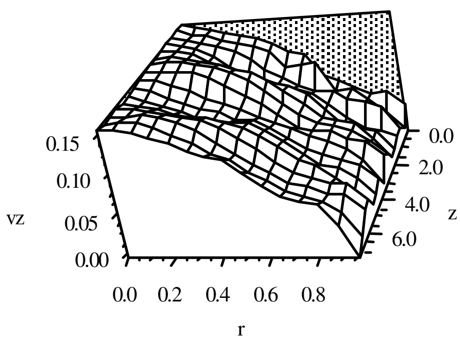
4. Results

The flow parameters $v_{\theta 0}$ = 0.2,1.0 and v_{z0} = 0.2,1.0 have been used in four separate runs. The essential physics is represented by the lower velocities, so we concentrate on these. The drag parameter α in Eq.(2) was chosen so that stationary velocities were reached in about 10 Alfvén times. Resulting velocity profiles are shown in Figs. 1 and 2.

Poloidal flow: The most important effect we are looking for is a reduction in turbulence. Thus we compare the radial magnetic field spectrum for the m=0,1,2 modes with those of our base run in Figs 3 and 4. Modes with negative toroidal mode numbers are resonant inside the reversal surface, vice versa. We see that m=0 and m=2 modes are somewhat suppressed, but the dominating m=1 modes essentially persist. This is reflected in $<B_r^2>$ (volume averaged), being essentially unaltered. Here β_θ=0.18, τ_E = 117 μs.

Axial flow: Just as for poloidal flow, the m=0 and m=2 modes are somewhat reduced. Comparing with the base case at the time the run ended, t=0.006τ_R, no improvement in $<B_r^2>$ is gained. The central rotation velocity is here 90 km/s, which just about equals the ion thermal speed. For this run β_θ= 0.18, τ_E = 93 μs.





Figs. 1 and 2. Flow velocity profiles for the cases $v_{\theta 0}$ = 0.2 (left) and v_{z0} = 0.2 (right).

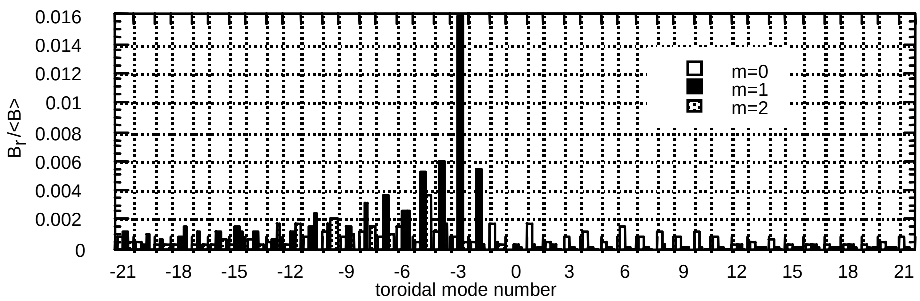


Fig. 3. Radial magnetic field spectrum, base case, normalized to the volume averaged magnetic field.

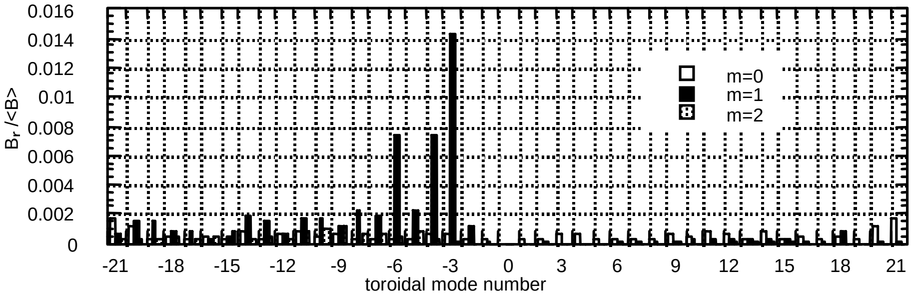


Fig. 4: Radial magnetic field spectrum, $v_{\theta 0}$ = 0.2 case.

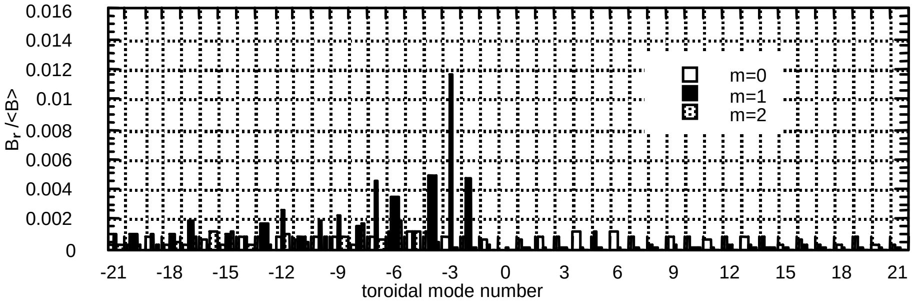


Fig. 5: Radial magnetic field spectrum, v_{z0} = 0.2 *case.*

5. Summary

The influence of sheared velocity flow on resistive turbulence in the finite beta RFP has been studied. Both poloidal and axial flow reduce m=0 and m=2 modes somewhat, but the persistence of the m=1 modes results in an essentially unchanged $\langle B_r^2 \rangle$. Further flow profiles need to be investigated, however, before a decisive conclusion can be drawn. Of particular importance are the dominant $n \approx 2R/a \approx 3$ tearing modes, being resonant in the core plasma. Current profile control (tearing modes) and kinetic stabilisation (resistive g-modes) may be necessary to reduce fluctuations to levels yielding acceptable confinement.

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