8. OTHER THEORY AND MODELLING STUDIES

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8.1. INTRODUCTION

This project included in 2004 three research lines:

- Study of the role of magnetic reconnection processes in the dynamics and confinement of thermonuclear plasmas;
- Modelling of Grad-Shafranov equilibria in tokamak plasmas.

8.2. ROLE OF MAGNETIC RECONNECTION PROCESSES IN THE DYNAMICS AND CONFINEMENT OF THERMONUCLEAR PLASMAS

8.2.1. Introduction

This research line included in 2005 studies on:

- The effect of sheared toroidal rotation on the stability of tearing modes;
- Error field driven reconnection.

8.2.2. Effect of sheared toroidal rotation on the stability of tearing modes

Magnetic reconnection events can degrade plasma confinement and limit fusion plasma performance. The physics of free reconnection, leading to the formation of magnetic island chains localised where the safety factor q(r) is rational, i.e. q=m/n, is a complex problem depending on many plasma figures of merit (collisionality, β_p) and profiles (pressure, current density). For plasmas discharges with significant Neutral Beam Injection (NBI), toroidal rotation could have a strong effect on tearing mode stability. In fact, in a scenario with sheared toroidal plasma rotation, the toroidal component of plasma velocity perturbations (negligible in static plasmas) is no longer expected to be negligible and should be taken into account for inferring mode stability even in a large aspect ratio machine.

Linear numerical MHD simulations in a cylindrical geometry with both perpendicular and parallel (to the equilibrium magnetic field) perturbations allow to conclude that plasma rotation in the equivalent toroidal direction can result both on the increase or decrease of the instability growth rate. A parabolic-like profile is considered for the toroidal rotation, vanishing at the plasma edge. Simulations were performed both for the single helicity model (that considers both parallel and perpendicular perturbations) and the conventional reduced MHD model (neglects parallel components of the perturbed quantities). Anomalous perpendicular plasma viscosity and plasma rotation shear at the modes' rational surface play a key role on assessing the effect of shear flow.

While destabilising for low viscosity plasmas (ratio of the resistive to viscous diffusion time scales τ_R/τ_V<<1) (Figure 8.1a), for viscous plasmas (τ_R/τ_V>1) shear flow reduces the growth rate, making possible mode stabilisation above a given rotation frequency (Figure 8.1b). Mode stabilisation is feasible owing to the considerable effect of the parallel component of the plasma velocity perturbations.

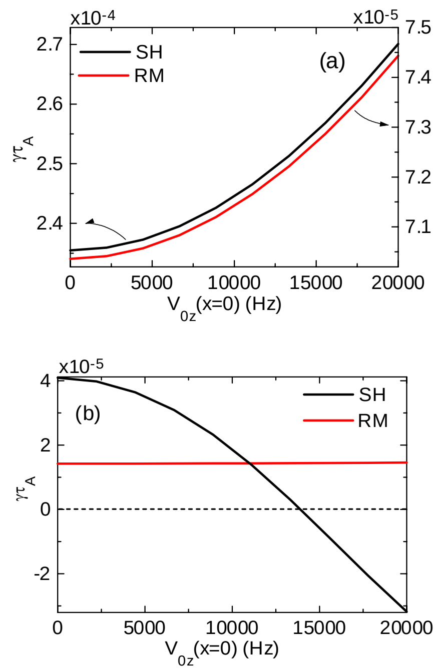

Figure 8.1 – Sheared toroidal plasma rotation is destabilising in low-viscous plasmas for both the single helicity and reduced MHD models (a) and stabilising in viscous plasmas (b).

When extrapolating to more reactor relevant operational conditions (higher Reynolds number S=τ_R/τ_A), one also notices that above a given threshold in the rotation shear (that decreases with increasing τ_R/τ_V) a tearing mode, unstable in the absence of rotation, can be stabilised (Figure 8.2). In addition, for the same ratio τ_R/τ_V, plasma rotation necessary for mode stabilisation decreases with increasing magnetic Reynolds number.

8.2.3. Error field driven reconnection studies

The penetration and amplification of static external magnetic fields on rotating magnetically confined fusion plasmas imposes serious limitations on the plasma performance, degrading confinement and potentially leading to some disruptions. To gain further insight on the physical mechanisms involved during this penetration, a detailed investigation was carried out. Two distinct

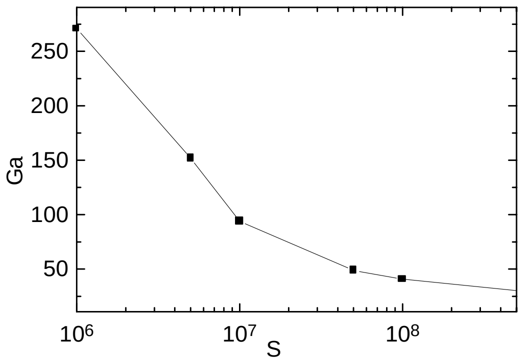

Figure 8.2 – Threshold in Ga (= τ_R/τ_V) for mode stabilisation as a function of the magnetic Reynolds number S for a rotating plasma with $V_{z0}(x=0)=20$kHz and aspect ratio $A=R_0/a=3.4$.

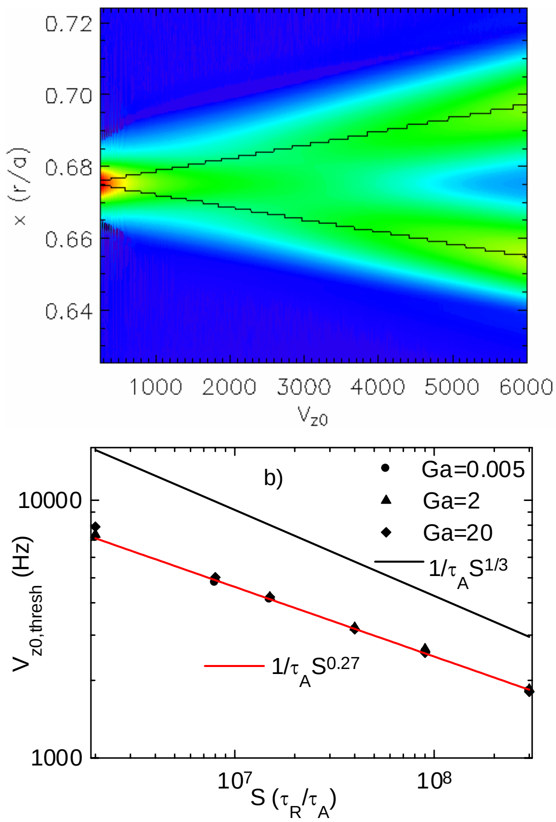

Figure 8.3 – Contour of the toroidal braking force exerted by static m=2,n=1 external magnetic fields on a rigid rotating plasma. Vertical axis indicates the radial direction and the plasma rotation lies on the x-axis (a). Rotation threshold for the transition between both regimes of reconnection (b).

regimes are found, depending on the plasma rotation frequency with respect to the static external magnetic windings producing the "error-field": a resistive-viscous regime, where plasma inertia plays a minor role in the reconnection; a viscous-ideal regime, where the reconnection layer is greatly affected by ideal MHD effects. The former regime is also known as Alfven Resonance regime (AR) since a resonance pair emerges at both sides of the q=m/n resonant tearing mode rational surface. These two resonances, spreading away from the q=m/n surface (q=2 in the simulations) as plasma rotation increases, play a significant role in the dynamics since they both shield magnetic reconnection at the q=m/n surface and are sinks for the transfer of angular momentum to the plasma. During the transition from a forced reconnection regime to an AR regime, the toroidal induced braking force is found to become an increasing function of plasma rotation frequency as a direct consequence of the emerging contributions at the AR locations, contrasting the decrease in the localised force at the q=2 surface (Figure 8.3). For a magnetic Reynolds number $S=3\times10^8$, transition to the AR regime occurs at ~1.8kHz when the force becomes increasingly localised at the Alfven resonances.

The threshold in plasma rotation for this regimes' transition scales as $\omega_{thr} \propto 1/\tau_A S^{0.27}$ and has a weak dependence on the anomalous plasma viscosity. It is conjectured that the lack of experimental evidence of an AR dominated regime in present tokamaks may be due either to an effective drag on plasma rotation caused by anomalous plasma viscosity or to the plasma collisionality regime (magnetic reconnection in a collisionless regime evolves on much faster time scales, implying a much larger threshold plasma rotation to enter the AR regime).

8.3. MODELLING OF GRAD-SHAFRANOV EQUILIBRIA IN TOKAMAK PLASMAS

The studies on *reversed Grad-Shafranov (GS) equilibria, with negative toroidal current density flowing in the core and overall positive plasma current*, were continued both via numerical simulations in more demanding conditions and by further theoretical developments. In particular, numerical solutions were found for some profiles where the toroidal current density assumes negative values in a location sufficiently off-axis (Figure 8.4) which are strong enough in order to develop two distinct poloidal-field reversal (PFR) layers, where the poloidal magnetic field does vanish (Figure 8.5). Contrary to currently available GS solutions in toroidal-current reversal scenarios, the considered configuration does not yield a central channel containing the magnetic axis where the current flows in a direction opposite to the one in rest of the plasma. Instead, it results in an annular region of negative current enclosing a positive current channel and being surrounded by positive currents also. Toroidal current-density profiles of this type are usually found in nonlinear resistive MHD simulations of JET plasmas with strongly reversed magnetic shear, but no GS equilibria was yet available for them. Besides showing the robustness of the scheme previously proposed to solve the GS equation for equilibria with toroidal current reversal, these are expected to help understand the physics behind the current-hole problem.

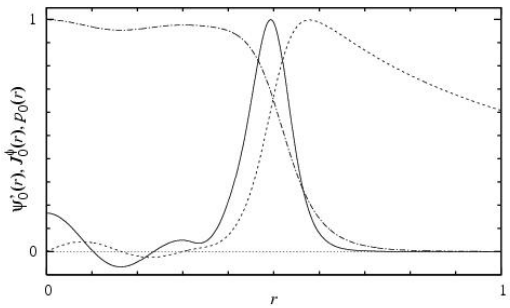

Figure 8.4 - Zeroth-order profiles $J^{\phi}_0(r)$ (solid line), $\psi'_0(r)$ (dashed line), and $p(r)=p_0(1+\alpha\, r)\exp(-\gamma\, r)$ for α=5.55 and γ =10 (dot-dashed line), normalized to their maximum values.

Following some previous work, a rigorous and consistent framework to describe *the topological features of reversed equilibria (nested and non-nested)* was developed by extending some fundamental concepts of Catastrophe Theory. This involved finding a suitable definition for nested equilibria, along with a systematic derivation of its most significant properties in current reversal scenarios. In general, these are extensions of results already established for isolated singularities of finite multiplicity, to manifolds of non-isolated singularities (such as the PFR layer) of infinite multiplicity. By rigorously showing that nested equilibria, on which most of the current knowledge is based, are non-typical and isolated elements, these results are expected to lead into a new paradigm when discussing GS solutions with toroidal current reversal.

In addition, it was noted that non-static configurations with non-vanishing poloidal and toroidal plasma flow could, at least in principle, force the toroidal current-density profile to display negative values. This led to efforts aiming to include finite plasma-flow effects in GS equilibria computations in order to assess their role in leading to reversed configurations.

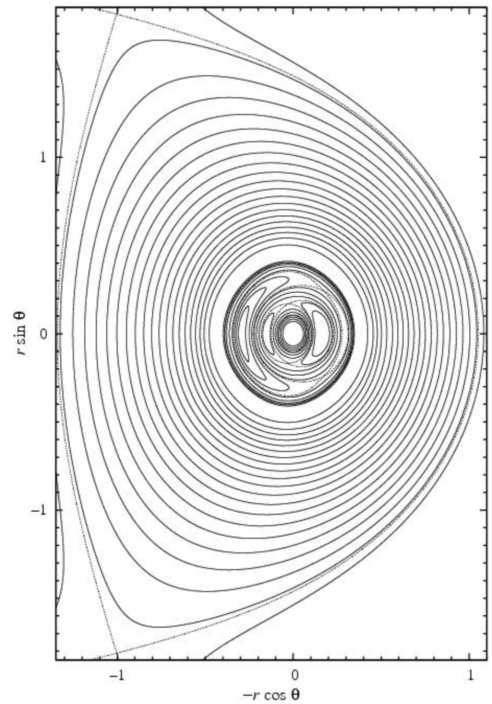

Figure 8.5 - Flux surfaces for typical JET parameters and the profiles depicted in Figure 8.4.