9. OTHER THEORY AND MODELLING STUDIES

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9.1. 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;
- Studies on lower-hybrid current drive;
- Modelling of Grad-Shafranov equilibrium in tokamak plasmas.

Concerning *the role of magnetic reconnection (ideal and resistive) processes in the dynamics and confinement of thermonuclear plasmas*[1], studies of the poloidal $\vec{E}\times\vec{B}$ velocity, mode coupling effects on plasma braking and NTM triggering and parity and topology of tearing mode perturbations have been carried out.

Regarding the *studies on non-inductive current drive*, a method to measure the scattering matrices of lower-hybrid multi-junctions has been developed. Progress has been made on the study of the spectral-gap problem for lower-hybrid current drive. IST/CFN staff has participated in the design of the ITER-like PAM launcher for lower hybrid current drive[2].

Concerning the *modeling of the Grad-Shafranov equilibrium in tokamak plasmas*, a perturbative GS equilibrium solver, able to deal with realistic pressure and current-density profiles, was adapted to handle the existence of a poloidal-field reversal layer, for which the tangential magnetic field and the enclosed toroidal current do vanish.

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

9.2.1. Introduction

The following main studies were performed in 2004:

- Poloidal $\vec{E}\times\vec{B}$ velocity (V_θ^{ExB}) studies;
- Mode coupling effects on plasma braking and NTM triggering;
- Parity and topology of tearing mode perturbations.

9.2.2. Poloidal $\vec{E}\times\vec{B}$ velocity (V_θ^{ExB}) studies

A further investigation on the effect of forced magnetic field line reconnection on plasma poloidal $\vec{E}\times\vec{B}$ velocity (V^θ_{ExB}) was conducted. The localised toroidal braking torque, driven by static external magnetic fields, that develops at the resonant q-surface inside the plasma for both the viscous-resistive and ideal-viscous regimes, is shown to be given by the generic form

$$T_\phi \propto \frac{(\delta\Omega\tau_{rec})^\lambda}{\beta^2+(\delta\Omega\tau_{rec})^\nu} \tag{9.1}$$

where the constant $\beta>1$, the parameters $\lambda=(1,1/4)$ and $\nu=(2,0)$, $\delta\Omega$ is the local plasma toroidal angular rotation variation and τ_{rec} is the characteristic reconnection time inside the viscous-resistive layer. It is shown that over the viscous time scale, although the localised torque spreads over a similar region both in the viscous-resistive and ideal-viscous regimes, the induced velocity gradient around the resonant surface (favourable to ITB onset) are smeared out. Thus, while differential rotation (shielding the external fields) is the most relevant mechanism preventing ITB formation in the viscous-resistive regime, plasma viscosity limits the maximum obtainable velocity shear in the ideal-viscous regime. It appears less likely that ITB onset in the vicinity of rational q=m/n surfaces may be connected to forced reconnection at such surfaces.

9.2.3. Mode coupling effects on plasma braking and NTM triggering

Magnetic field line reconnection events are potentially hazardous since they may deteriorate the plasma energy confinement and performance. In particular, the onset and growth of neoclassical tearing modes (NTMs), a resistive instability driven by the loss of the bootstrap current fraction within the island chain associated to this instability, is known to limit the maximum achievable plasma beta and prevent safe access to relevant advanced regimes of tokamak operation. Another event that strongly affects confinement, potentially leading to plasma disruptions, is the penetration and amplification of locked modes induced by the intrinsic “error-field” of the machine. Both types of magnetic perturbations are a major concern for a reliable operation of next stage tokamaks such as ITER and for future tokamak fusion reactors.

Mode coupling, through driven reconnection, can drive the NTM island width up to the bifurcation threshold even when there is differential rotation. In such a scenario, the mode frequency evolution is complex and as soon as the island width overcomes the bifurcation threshold, the mode decouples from the coupling drive and acquires its natural rotation frequency (Figure 9.1). Focusing on the role played by mode coupling on the global, self-similar, plasma rotation braking that favours the amplification of locked modes induced by the intrinsic tokamak error-field, it was enlightened that, although toroidal and non-linear mode coupling contribute to a non

[1] Work carried out in collaboration of CNR-Milano, of the Association EURATOM/ENEA. Contact Person: E. Lazzaro.
[2] Work performed in collaboration with the Association EURATOM/CEA.

localised braking of the toroidal rotation around the resonant surfaces inside the plasma (Figure 9.2), coupling to plasma elongation appears to be essential to explain the experimental observations.

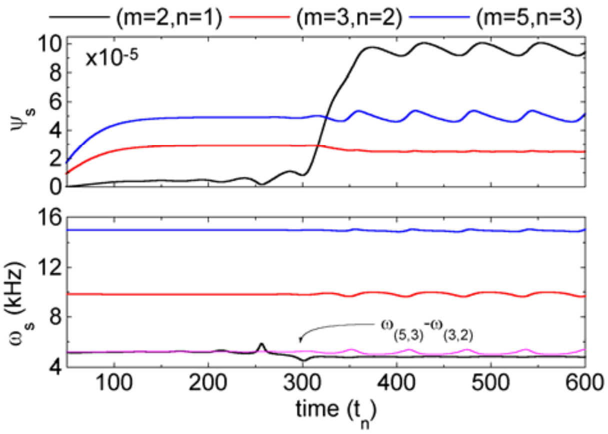

Figure 9.1 - Metastable m=2,n=1 mode triggering and destabilization by nonlinear three wave resonance mode coupling to (3,2) and (5,3) modes.

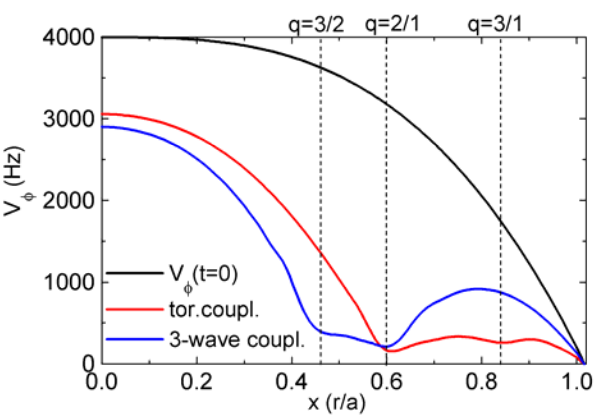

Figure 9.2 - Reduced MHD numerical calculations evidencing the additional plasma braking due to three wave (with driving (2,1) and (3,2) modes) and toroidal coupling (with the (3,1) mode) with a dominant m=2,n=1 error field driving component.

9.2.4. Parity and topology of tearing mode perturbations

The dominantly sheared toroidal plasma rotation (affecting the $\vec{E}\times\vec{B}$ velocity) that is imparted by neutral beam injection can benefit plasma confinement, reducing the scale length of turbulence, shielding plasma reconnection driven by the error-field and stabilising resistive wall modes. Resistive modes, such as the tearing mode, may nonetheless be unstable, deteriorate plasma confinement and eventually lead to disruptions. The effect of toroidal rotation on the reconnection rates and tearing eigenfunctions, as well as on the topology of the rotation and flux contours associated to tearing modes, in a small/medium aspect ratio low-β cylindrical tokamak was addressed.

A single helicity symmetric cylindrical model, valid for all aspect ratios but with imposed incompressible plasma motion was adopted and the reconnection rate dependence on the aspect ratio and on the sheared toroidal rotation was firstly investigated. The magnetic and velocity perturbations parallel to the helical versor at small aspect ratio, are shown to destabilise ideal modes, rendering the growth rate of the fastest m=1,2 growing modes independent of the Reynolds numbers (Figure 9.3).

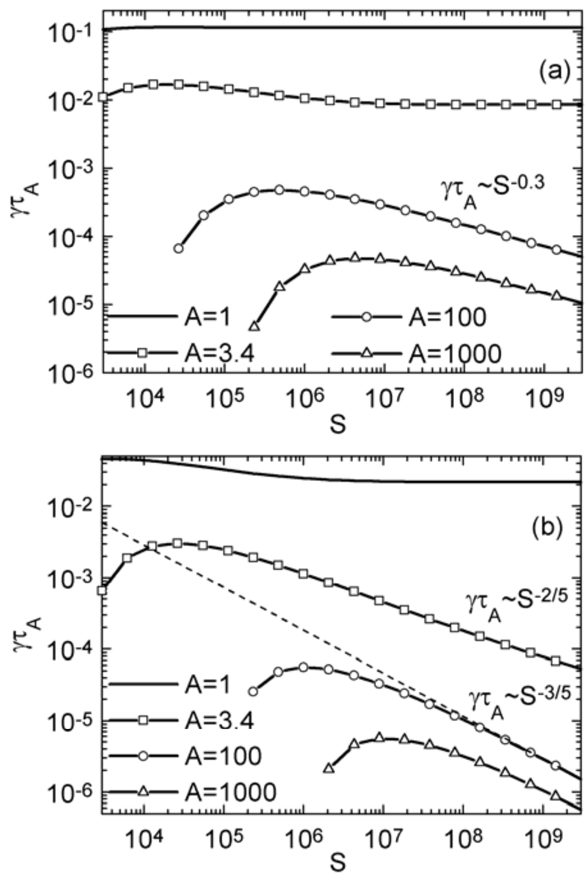

Figure 9.3 - Growth rate scaling of m=1 (a) and m=2 (b) tearing instabilities with the magnetic Reynolds number for several values of the aspect ratio A.

Plasma angular rotation is also shown to have a strong influence on the stability of tearing modes, dependent on the Prandtl number (ratio of the resistive to viscous diffusion times). For low viscosity scenarios (Prandtl <<1), toroidal rotation profiles with decreasing velocity with plasma radius are found to destabilise the mode, doubling the growth rate when rotation is of the order of 20kHz at the magnetic axis. On the other hand, for Prandtl>>1 (typically of the order 10), plasma rotate with the same type of radial profile but with 13 kHz at the magnetic axis is sufficient to stabilise the mode. Sheared plasma rotation and viscosity were also found to have a profound effect on the topology of the ohmic unstable magnetic island. In fact, for high Prandtl numbers, the island appears deformed as soon as it forms, becoming symmetric only when reaching a steady state. For low viscous plasma the deformation is much smaller.

9.3. STUDIES ON LOWER-HYBRID CURRENT DRIVE

9.3.1. A method to measure the scattering matrices of lower-hybrid multijunctions

Aiming at routinely and reliably testing the S-matrices of the multijunctions that build up lower-hybrid (LH) antennas, a general method for measuring the S-matrices of microwave (mW) devices with any number of ports has been developed using basic network analysis. The broader approach used in this work may prove eventually useful to anyone interested in measuring S-matrices of arbitrary mW components. In fact, such method has been proposed, and is going to be adopted, to test the multijunctions that will build up the ITER-like PAM launcher to be eventually installed on JET.

9.3.2. Progress on the spectral-gap problem for lower-hybrid current drive

One of the possible solutions for the so called spectral-gap problem on the LH current drive could be the effects of the magnetic ripple on the LH wave propagation in plasmas. To correctly assess the extent of these effects in real tokamaks, a fully consistent 3D toroidal equilibrium with magnetic ripple has to be assessed, which can only be done via a numerical solution. A parallel 3D equilibrium code has been developed using a new approach based on a generalized non-conservative variational principle, assuming nested flux surfaces and compatible with fixed or constrained almost-free plasma boundary.

9.3.3. Design of an ITER-like PAM launcher for lower-hybrid current drive

Two main actions were carried out in the framework of the collaboration with CEA-Cadarache on heating and current drive: the studies of a PAM (Passive Active Multijunction) ITER-like LHCD launcher for Tore Supra and the initial studies of a similar launcher for JET.

On the subject of the launcher for Tore Supra the following work was carried out: study of the impact that a vacuum gap inserted between the antenna mouth and the plasma has on the directivity and the coupling properties of the PAM as a function of both the vacuum gap width and the plasma density (above the plasma cut-off density); determination of the effect that the use of passive waveguides with depths different from the original design ($\lambda/4$) have on the directivity and coupling properties of the PAM and, in particular, when combinations of passive guides with distinct depths is used; the phase shifters were appropriately compensated for to take into account the toroidal as well as poloidal shape of the mouth, the RF properties of the first TE_{10}-TE_{30} mode converter prototype were experimentally determined by a team at CEA-Cadarache and the mode converter (as well as the structure used in the corresponding experimental set-up) was then modelled in order to compute the theoretical RF properties and compare them to the measurements; further developments and improvements were introduced to the three new codes (started during the previous year) that are meant to study the stability of the system made up of the PAM + mode-converter.

The preliminary studies of a PAM-type antenna for JET were also started in response to a call from the EFDA Associate Leader for JET relating to the upgrade activities of its LHCD system (a project for which CEA-Cadarache contributes as the Leader Association). This work focused primarily on the coupling and directivity properties of two launcher designsand a variety of studies were carried out. As a conclusion of this work the bijunction was proposed for the design of the PAM type antenna.

9.4. MODELLING OF THE GRAD-SHAFRANOV EQUILIBRIA WITH NEGATIVE CORE TOROIDAL CURRENT IN TOKAMAK PLAMAS

The possibility of reversed Grad-Shafranov (GS) equilibria, with negative toroidal current density flowing in the core and overall positive plasma current, attracted considerable discussion in the fusion community, mainly in connection with improved confinement regimes displaying strongly reversed magnetic shear. Although some of their properties have already been established for a few particular choices of pressure and current-density profiles, a suitable framework was lacking which could provide physical insight into the problem, as well as numerical solutions for more general input profiles. To this end, a perturbative GS equilibrium solver, able to deal with realistic pressure and current-density profiles, was adapted to handle the existence of a poloidal-field reversal (PFR) layer, for which the tangential magnetic field and the enclosed toroidal current do vanish.

It has been explained why reversed equilibria with nested topology are isolated and hardly realizable, as opposed to more structurally stable non-nested solutions (Figure 9.4).

In addition, the island system that unfolds, with its separatrix, in these reversed equilibria is suitably shaped by tailoring the pressure and poloidal-field input profiles (Figure 9.5), a task which is greatly simplified by the ability of the adapted GS solver to handle general input profiles.

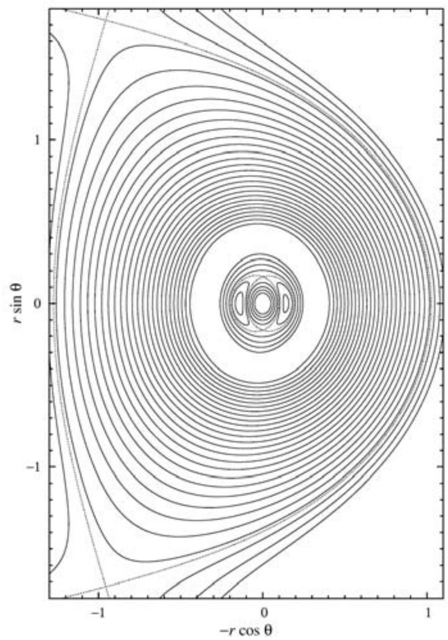

Figure 9.4 - Flux surfaces for typical JET parameters and pressure profile $p(r)=p_0(1-\alpha r)\exp(-\gamma r)$ with $\alpha=9.5$ and $\gamma=10$.

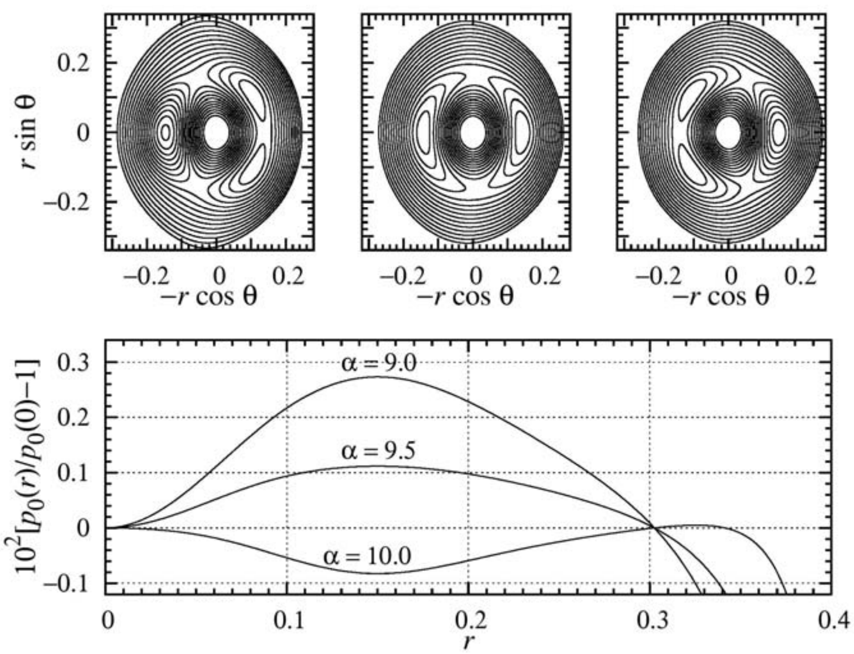

Figure 9.5 - Flux surfaces at the core zone for three different pressure profiles with α=9.0, 9