7. STUDIES ON TRANSPORT AND MHD ACTIVITY

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7.1. INTRODUCTION

The activity of this project has been focussed in the following research lines:

- Influence of mode coupling on the non-linear evolution of rotating magnetic islands
- MHD activity and loss of confinement in JET radiative mantle experiments
- Influence of sawtooth pre-cursors at the onset of neo-classical tearing modes
- Effect of plasma rotation on sawtooth stabilization by neutral beam injection
- Internal kink stability analysis of JET impurity seeded discharges

The work related to the last four research lines have been performed under the JET Implementing Agreement and is described in the chapter III.

7.2. INFLUENCE OF MODE COUPLING ON THE NON-LINEAR EVOLUTION OF ROTATING MAGNETIC ISLANDS

7.2.1. Introduction

This work has been carried out in collaboration with the Istituto di Física del Plasma (CNR, Milan, Italy) and was focused on the non-linear interaction of external currents with both stable and unstable tearing modes, using a non-linear reduced (RMHD) initial value code developed for the study of rotating tearing modes with various boundary conditions and suitable for the investigation and testing of stabilisation mechanisms.

The following main topics have been addressed:

- Effect of mode coupling on the triggering and control of neo-classical tearing modes
- Analytical and numerical studies on the ohmic and neoclassical tearing mode flipping
- Innovative interpretation of tearing mode locking to an external resonant error-field
- Non-linear RMHD calculations of tearing mode stabilisation using radio frequency electron cyclotron waves
- Multiple helicity non-linear RMHD calculations of triplet mode coupling interaction

Applications have been made to both FTU and JET plasmas.

7.2.2. Effect of mode coupling on the triggering and control of neo-classical tearing modes

The mechanism for triggering MHD modes around a sawtooth crash is still an open problem of tokamak physics. Inspection of high resolution magnetic data in either ELM-free or ELMy regimes shows clearly that in many discharges the onset of modes often interpreted as sawtooth "post-cursors" actually occurs before the sawtooth crash. This excludes the crash itself as the triggering mechanism and on the other hand it suggests that mode coupling may play an important role in the destabilisation of these modes.

We have considered the effect of toroidal and non-linear coupling on the marginal stability of neo-classical tearing modes (NTMs) observed in the JET ELMy regime. In those discharges with high beta the conditions are close to the threshold for destabilisation of NTMs. Accordingly, we formulated the problem of assessing the conditions for driving a seed island above threshold, by linear or non-linear coupling of modes.

The models for mode coupling were derived as an extension of the large R/a Rutherford theory of non-linear tearing modes. In the non-linear coupling problem, triplets of rotating magnetic islands with different toroidal numbers are considered. Here the driven term for a (3,2) NTM is the (1,1) sawtooth pre-cursor. We considered the following sequence of events. Initially, the local β^{θ} for the driven mode (3,2) and a passive mode (4,3) is raised by the auxiliary heating above or marginally above the critical value for onset of neo-classical tearing instability. The seed island width, W_{seed}, of the (3,2) mode is initially below the threshold value, therefore the grow-rate $\Gamma_{3,2}^{(0)}(W_{seed}) \leq 0$ preventing the appearance of the instability. As the main driving mode (1,1) grows to sufficiently large amplitude driven by its own free energy, the non-linear coupling produces a perturbation of the rate of growth of the type

$$\Gamma_{3,2}(W_{3,2}, W_{1,1}, W_{4,3}) = \Gamma^{(0)}_{3,2}(W_{3,2}) + \Gamma_{coupl}(W_{3,2}, W_{1,1}, W_{4,3}, \cos\Delta\phi)$$

driving the instability by making the global

$$\Gamma_{3,2}(W_{seed}, W_{1,1}, W_{4,3}) > 0$$

for the same seed island. (Here $\Delta\phi$ is the phase difference between the interacting modes). The non-linear coupling term of the triplet combination considered is, where p,q and r are the toroidal numbers of the interacting modes. The same reasoning applies in the case of toroidal coupling, where the (3,2) mode is driven by the (2,2) harmonic of the (1,1) sawtooth precursor. In this case, the form of the toroidal coupling term of mode (m,n) with mode (m+1,n) is

$$\Gamma_{coupl}(W_{m+1}, W_m, \cos\Delta\phi) = \frac{r_s^2}{\tau_{R,m+1}} \frac{(m+1)}{R} \left(\frac{r_{sm}}{r_{s(m+1)}}\right)^m \frac{h_m}{h_{m+1}} \frac{W_m^2}{W_{m+1}^2} \cos\Delta\phi$$

Application to JET experimental plasma profiles shows that either toroidal or non-linear coupling are effective mechanisms, of comparable order, to trigger neoclassical tearing modes.

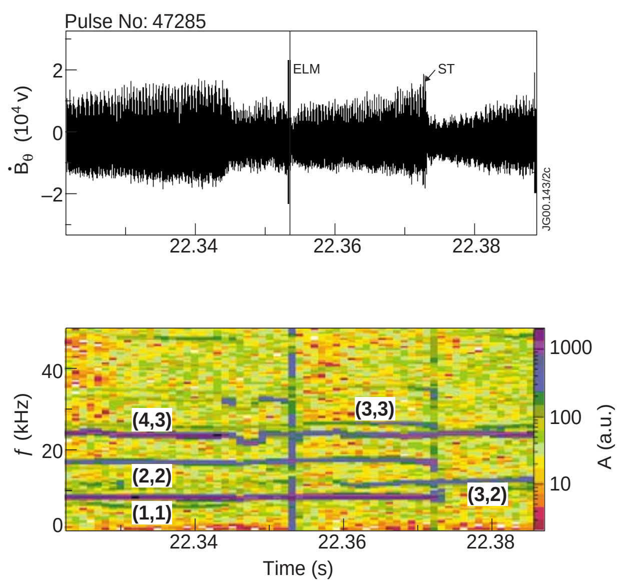


Fig. 7.1 – a) Magnetic signal and, b) Spectrogram showing the frequency and amplitude of modes observed around a sawtooth crash. It shows the sawtooth precursor (1,1) and its harmonics (2,2) and (3,3), a (4,3) mode unaffected by the sawtooth crash and the onset of a (3,2) mode observed above the noise level at 15 ms before the sawtooth crash.

7.2.3. Analytical and numerical studies on the ohmic and neoclassical tearing mode flipping

A major limit to steady state and advanced high β_p operation of tokamaks of reactor class is due to the onset of *dissipative modes* that develop magnetic islands and may cause loss of energy confinement or a major disruption. External resonant control helical fields are considered to be a robust and conceptually simple stabilisation mechanism. Although a lot of work has been done on its merit and potentiality, small importance is given to its limitations and structural stability. In fact, both RMHD and analytical Δ'-model calculations show that the external field current, in phase with the mode in its rest frame, cannot be arbitrarily large so as to suppress the mode completely. There is a maximum absolute magnitude for this current after which the mode flips towards a more unstable solution (Fig. 7.2). In addition, the minimum stable island width W (where $W \propto \sqrt{\psi_s}$ and ψ_s is the reconnected magnetic flux at the rational surface of the mode under consideration) which can be obtained is finite and, depending on the plasma profiles, may be just half of the unperturbed value.

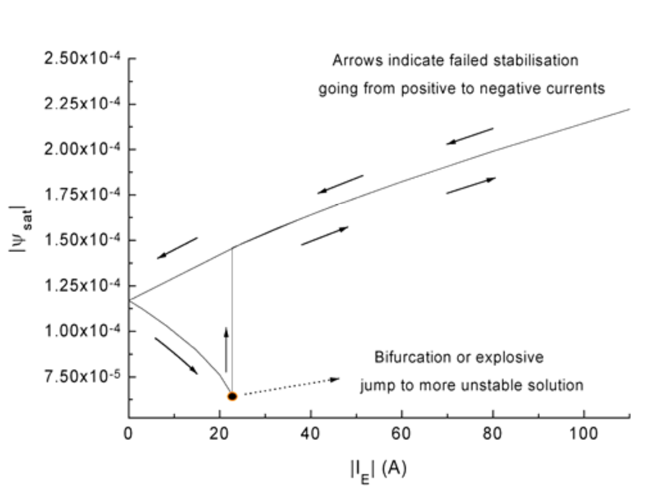


Fig. 7.2 - Normalised magnitude of reconnected (m=2,n=1) flux $|\psi_s|$ vs magnitude of external control current $|I_E|$ for a q_0=1.2 and q_a=4.2 parabolic q-profile FTU-type discharge, calculated by a full non-linear tearing mode code in large R/a approximation

The same bifurcation analysis can be carried out for neo-classical tearing modes, a special king of modes which are driven unstable by the local loss of the bootstrap current density fraction and that limit the β_p operational limit. When the ion polarisation current stabilising effect is neglected, a generic equilibrium manifold is obtained (Fig. 7.6), unveiling a novel and fundamental understanding of the mechanism of trigger of a neoclassical mode by external ("error") helical fields or equivalent source. As the control parameter (external current) changes, the mode amplitude increases passing through a sequence of equilibrium states saturated at a very small values. However when a threshold in the external current is passed the system undergoes a tangent bifurcation and the mode explodes toward a high saturated equilibrium amplitude.

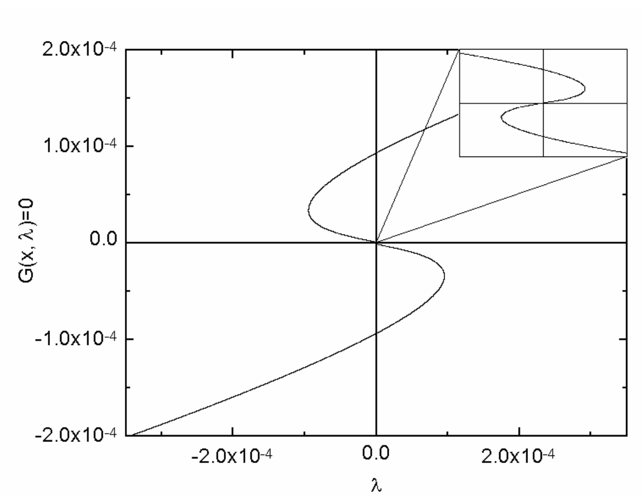


Fig. 7.3 - Equilibrium manifold $G(X=\psi_S,\lambda\propto I_E)=0$ vs the control variable λ for "neoclassical" tearing mode model. The tangent bifurcation points and the local generic structure are apparent in the insert.

When we include a finite albeit small ion polarisation current effect, the situation is substantially changed. The equilibrium manifold shown in Fig. 7.4 is not generic as in the previous cases. It shows that because of this effect, the slightly saturated states are no longer accessible and to reach a saturated equilibrium a threshold value scaling as $\psi_{thr} \propto \lambda^{-1}$ must be overcome by an initial *seed island*. This means also that the flip bifurcation is prevented except at vanishing of the ion polarisation term.

7.2.4. Innovative interpretation of tearing mode locking to an external resonant error-field

Many disruptions occurring in toroidally rotating plasma discharges of several tokamak devices are preceded by growing static helical magnetic perturbations. In some cases, naturally unstable rotating tearing modes, under the influence of the static error-field, cannot sustain their rotation and are eventually brought to rest, being further destabilised.

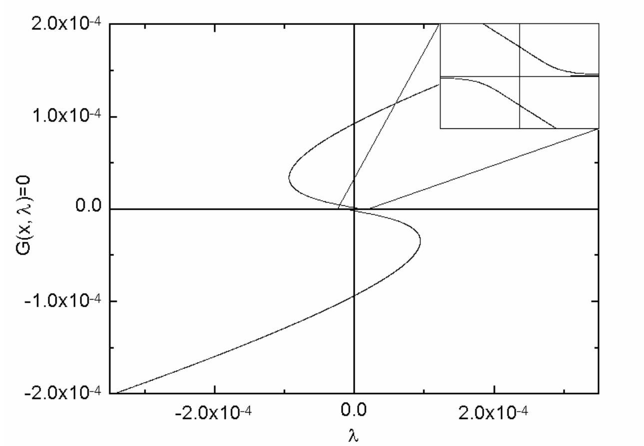


Fig. 7.4 - Equilibrium manifold $G(X=\psi_S,\lambda\propto I_E)=0$ vs the control variable λ for "neoclassical model with ion polarisation current" The insert shows the non generic structure.

The conventional approach to explain the locking of a rotating tearing mode to an external static field resonant with the mode is based on the calculation of the toroidal torque due to the external field, entering the angular momentum balance equation of the rotating island. Within this approach, any mode frequency deviation from its natural frequency must be accompanied by an equivalent toroidal plasma rotation modification, in order to satisfy a no-slip condition, i.e. the plasma is frozen inside the island. Although this may be the case for very high magnetic Reynolds number ($S>>10^8$), for medium size toroidal machines such as FTU the no-slip condition may not necessarily be satisfied.

A general dispersion relation for rotating tearing modes interacting with a static external error-field has been developed and is summarised in Equation:

$$\omega(x,t) = \frac{\eta}{S}\nabla_0^2\phi + \frac{2\eta}{S}\cdot\frac{\partial\phi}{\partial x}\cdot\frac{\partial \ln|\psi|}{\partial x} + p(x)\cdot \frac{|u|}{|\psi|}\cdot\cos(\varphi(x,t)-\phi(x,t)) + \frac{n}{\varepsilon}\cdot v_z$$

The perturbed magnetic field and plasma velocity are given, respectively, in terms of the poloidal magnetic flux (ψ) and stream function (u) and ϕ(x,t) and φ(x,t) are the phases of the complex valued

$$\psi \equiv |\psi(x,t)| \cdot e^{i\phi(x,t)}$$

and

$$u \equiv |u(x,t)| \cdot e^{i\varphi(x,t)}.$$

The (m,n) mode frequency is given by

$$\omega \equiv \frac{\partial \phi}{\partial t}$$

and we defined

$$p(x) \equiv \frac{m - n.q(x)}{\varepsilon.q(x)}$$

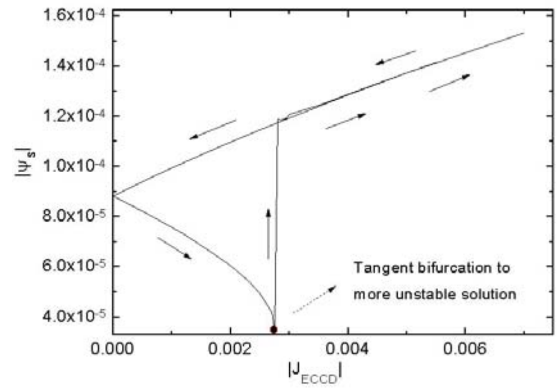
where q is the usual q-profile and ε the aspect ratio. The external current forces a gradient in ϕ at the plasma edge, which propagates inwards up to a layer of very fast phase variation (slipping layer). Mode locking was found to occur when this layer coincides with the tearing layer.

A novel interpretation of mode locking was thus obtained, which indicates that the mode frequency obeys a particular dispersion relation rather than following the toroidal plasma velocity at the rational surface. In fact, it is the mode frequency time evolution, which, via electromagnetic torques, controls the toroidal plasma velocity evolution.

7.2.5. Non-linear RMHD calculations of tearing mode stabilisation using radio frequency electron cyclotron waves

It has been demonstrated that by carefully depositing rf-waves with the electron cyclotron frequency in the vicinity of the rational surface of a given neoclassical tearing mode, one can completely suppress the mode. This is achieved both by ECRH (Electron Cyclotron Resonance Heating) and ECCD (Electron Cyclotron Current Drive) effects. Both effects drive a localised helical current density with a relative phase to the rotating island. O-point current drive stabilisation is observed to be more efficient than X-point current drive destabilisation and therefore even an un-phased scheme is able to stabilise the mode significantly. With such un-phased schemes and with vanishing ion polarisation effects, we may also avoid mode flipping (Fig. 7.5), an essential feature of phased schemes, shared also by phased external current stabilisation schemes.

In addition to driving a helical current inside the island, the rf-waves deposition may also modify the surrounding plasma temperature, thereby modifying the plasma electrical conductivity. The equilibrium axisymmetric toroidal plasma current can therefore diffuse and modify the current density gradient at the rational surface, a key ingredient in tearing mode stability. This effect was investigated to provide an idea of the potentiality of such stabilisation method in strong ECRH FTU campaigns, and is summarised



in Figs. 7.6a and 7.6b where the saturated

Fig. 7.5 - Normalised magnitude of reconnected (2,1) flux $|\psi_s|$ vs magnitude of driven current $|J_{ECCD}|$ for a q_0=1.5 and q_a=3.5 parabolic q-profile FTU-type discharge, calculated by a full non-linear tearing mode code in large R/a approximation.

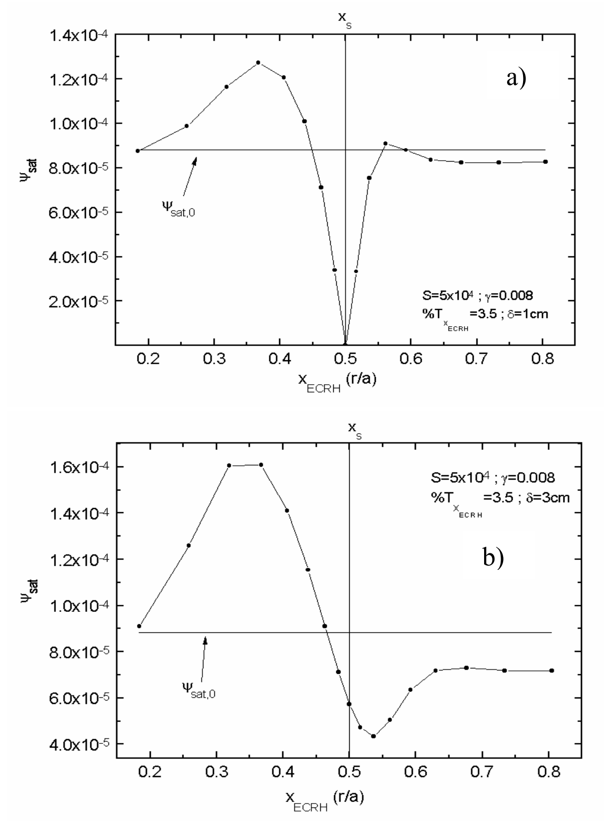


Fig. 7.6 - Normalised magnitude of reconnected (2,1) flux Ψs vs radial ECRH deposition: (a) for a deposition width of 1 cm, (b) for a deposition width of 3 cm, and for a q_0=1.5 and q_a=3.5 parabolic q-profile FTU-type (low viscosity γ) discharge, calculated by a full non-linear tearing mode code in large R/a approximation.

reconnected flux is plotted as a function of the ECRH power deposition radial location, for two different ECRH profile widths. A larger stabilisation effect is observed for narrower deposition profiles. Nonetheless, stabilisation is only achieved if one heats the plasma outside ($x \geq x_s$) since this tends to flatten the current density profile.

7.2.6. Multiple helicity non-linear RMHD calculations of triplet mode coupling interaction

The non-linear development of high (m,n) tearing modes which should in principle be stable is observed experimentally in a tokamak plasma . The RMHD numerical code was thus extended to include the non-linear mode coupling between modes of different helicity, satisfying a three-wave mode resonance. Preliminary results show that low central shear q-profiles, which are unstable to (2,1) and (3,2) modes, can significantly drive a (5,3) mode, locking its frequency to the sum of the other two modes. Further investigation is necessary to study which profiles are significantly unstable and to make a comparison with experimental results, where possible. Collaboration with the RFX project (Padova) has already been discussed although a new version of the code, suitable for reversed field pinch equilibrium, would have to be developed.