Mode Coupling Effects on the Triggering of Neoclassical Tearing Modes and Plasma Momentum Braking

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Abstract. Plasma energy confinement and performance may be deteriorated by the onset and growth of neoclassical tearing modes (NTMs) and by the penetration and amplification of locked modes induced by the intrinsic “error-field” of the machine. In this work, it is shown that electrodynamic mode coupling may be important in explaining some crucial details regarding these two instabilities. In particular, we show that mode coupling can effectively trigger some NTMs, despite a finite frequency mismatch between the modes’ and coupling driven frequencies, as inferred from the magnetic diagnostics. In addition, we show that the toroidal plasma rotation braking following the penetration and amplification of error-field driven (m=2,n=1) locked modes is strongly affected by mode coupling, in particular due to the contribution of plasma elongation.

1. Introduction

A good understanding of the plasma dynamics and stability of tokamak confinement devices is essential for the progress towards a controlled, clean exploitation of fusion power. 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) [1], 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 [2]. 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 [3]. 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.

In a toroidally confined plasma with noncircular shaping, the electromagnetic coupling between plasma perturbations with different wavenumber is inevitable. In fact, owing to the toroidal symmetry and noncircular plasma shape, the metric elements’ (of the plasma geometry) dependence on the poloidal angle is such that a magnetic perturbation with poloidal and toroidal mode numbers (m,n) drive, through coupling, sideband perturbations with m±1,2,3, where the linear coupling is induced, respectively, by the plasma toroidicity, elongation and triangularity [4]. In addition, independently of the plasma symmetry and shape, modes with different (m,n) wavenumbers can couple non-linearly to drive a third mode, satisfying a three-wave matching condition, i.e. $(m'',n'') = (m,n) + (m',n')$ [5]. The investigation of both the physics behind NTM triggering and of the toroidal plasma momentum dynamics following the penetration of error-field locked modes offers a clear indication of the impact that mode coupling may have on plasma stability and rotation.

2. Destabilization of Neoclassical Tearing Modes by Mode Coupling

While considerable progress has been made in understanding the physical mechanisms imposing a threshold for the NTM destabilisation [6,7] and developing robust feedback stabilization schemes [8], the physical mechanism behind the triggering of the mode is still an unsolved problem. There is strong consensus that these modes are metastable, requiring a threshold island width to be crossed, above which the perturbation (and thus the island) will grow. One possible explanation is that, when the plasma beta rises, the mode can be driven unstable by a rapid increase in the linear tearing stability index Δ' just before onset [9]. There is also strong evidence that the onset of these modes often occurs in the vicinity of a sawtooth crash, although not necessarily in coincidence [10]. It is therefore plausible that, through electro-dynamic mode coupling to other existing modes, the m=1 mode precursor of the sawtooth can indeed play a significant role in driving the seed island above the threshold for NTM destabilization.

In Ref. 11, analysis of JET #47285 discharge, evidencing the onset of a (3,2) NTM, and numerical predictions from both three-wave resonance and toroidal mode coupling Δ'-models, has indicated that three-wave coupling between the (m=1,n=1) sawtooth precursor and a pre-existing (m=4,n=3) could potentially drive the (m=3,n=2) mode beyond the threshold for irreversible destabilization (see Figure 1) [11].

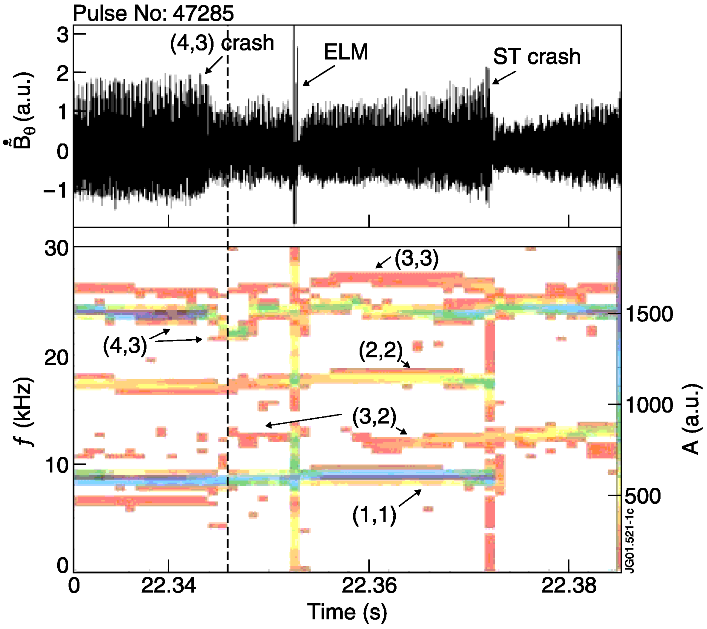

Figure 1 – Destabilisation of a (3,2) NTM by induced three wave coupling with the (1,1) and (4,3) modes [11].

This mode coupling hypothesis as a triggering mechanism may sometimes be counterintuitive since quite often a frequency mismatch between the NTM, once it is observed in the diagnostics, and the driving coupling frequency is observed experimentally. Although reducing the strength of the coupling effect prior to the mode bifurcation, this does not *a priori* exclude coupling as the NTM triggering mechanism. In fact, as explained in Ref. 12, as soon as the driven island width overcomes the bifurcation threshold, smaller than the metastable NTM threshold, the angular mode frequency need not be that imposed by coupling. Magnetic or ECE diagnostics capable of tracking an island smaller than the NTM threshold should remove these doubts concerning frequency evolution and the role of coupling as triggering mechanism. This is shown in Figure 2, where the numerical results regarding the destabilisation of a metastable (2,1) mode, driven by coupling to artificially driven (5,3) and (3,2) modes is shown. A cylindrical reduced MHD model is used with a sheared toroidal plasma rotation profile such that there is a differential rotation between the driving frequency ($\omega_{(5,3)} - \omega_{(3,2)}$) and the natural rotation frequency of the (2,1) mode in the absence of coupling. The reconnected flux at each rational surface (ψ_s) is related to the island width (W) by $W \propto \sqrt{\psi_s}$.

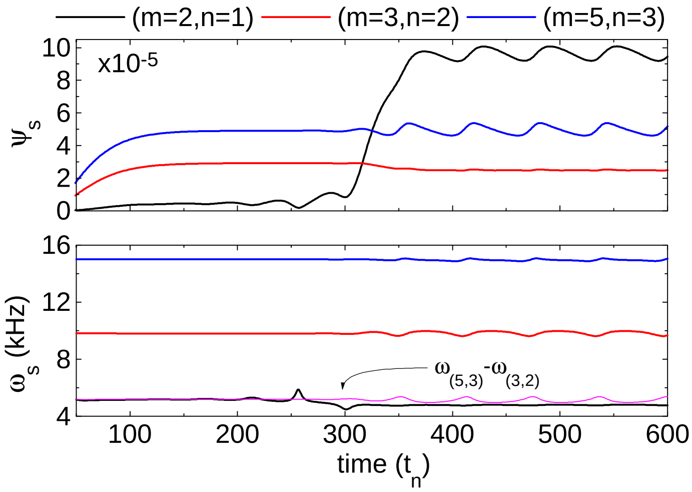

Figure 2 – Metastable m=2,n=1 mode triggering and destabilization by nonlinear mode coupling to (3,2) and (5,3) modes.

3. Toroidal Rotation Braking Driven by Mode Coupling

The penetration and amplification of locked modes induced by the intrinsic "error-field" of a tokamak can impose stringent conditions on the operation of future fusion reactors. The threshold for mode penetration depends on key plasma parameters such as the angular rotation imparted by the Neutral Beam Injection (NBI) at the resonant surface (ω_s), the plasma density (n) and the toroidal magnetic field (B_ϕ). An approximate scaling law that fits reasonably well some JET data is given $b_{pen}/B_\phi \sim n^{0.583}B_\phi^{-1.274}\omega_s^{0.5}$ [13]. While an increase in the toroidal magnetic field is clearly detrimental, plasma rotation increases the error field amplitude threshold for mode amplification by opposing reconnection. Therefore it is important to understand the physical mechanisms involved in the rotation braking induced by the error field.

When the dominant m=2,n=1 static error field component interacts with the rotating plasma, neglecting coupling effects, a localised torque is driven at the resonant q=2 surface, assumed inside the plasma. This leads to a localised braking of plasma rotation around the q=2 surface, in contradiction with some experimental evidence [13] that shows a more global braking, distributed over the entire plasma radius and inconsistent with a diffusive model based purely on the joint effect of electromagnetic $\mathbf{J}\times\mathbf{B}$ and perpendicular anomalous viscous torques. Intuitively, one should expect that, when mode coupling to other perturbations resonant inside the plasma (three wave or toroidal) is taken into account, a broader braking effect is observed. Yet, the total braking force should be interpreted merely as the sum of various localised forces, each at its' own location inside the plasma. In Figure 3, we show the numerical results, using a reduced MHD code, of the non linear and toroidal coupling effects on toroidal plasma rotation (V_ϕ), when a dominant (2,1) static error field component is driving reconnection at the q=2 surface. The two coupling curves show the radial profile of the toroidal plasma angular rotation after the m=2 mode has amplified and brought down significantly the plasma rotation. In the non-linear coupling, the error field driven (m=2,n=1) and an artificially driven static (m=3,n=2) couple to drive other modes with different helicites m/n. A coupling between the m=2 and m=3 modes is assumed for the toroidal coupling. Despite its non negligible role, non-linear and toroidal mode coupling effects are not sufficient to explain the self-similar rotation collapse (*i.e.* $V_\phi(r,t>t_0)=k(t)V_\phi(r,t_0)$ where penetration is considered to occur at t_0).

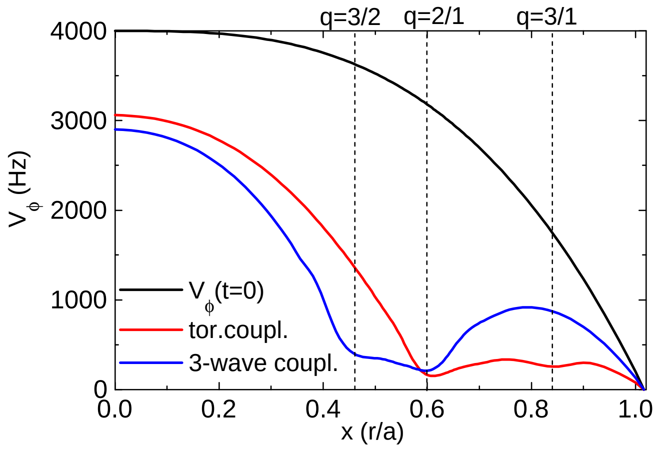

Figure 3 – Reduced MHD numerical calculations evidencing the additional plasma braking due to three wave and toroidal coupling with a dominant m=2,n=1 error field driving component

In order to explain this collapse, it is instructive to analyse the flux surface averaged motion equation along the toroidal direction,

$$\rho\frac{\partial V_\phi}{\partial t}=\left\langle \hat{e}_\phi\cdot\mathbf{J}\times\mathbf{B}\right\rangle-\left\langle \hat{e}_\phi\cdot\nabla\cdot\overleftrightarrow{\Pi}\right\rangle+\nu\nabla^2(V_\phi-V_{\phi,t=0}) \quad (1)$$

where the second term on the right hand side represents the toroidal neoclassical viscous force and the last one the restoring viscous drag [14]. The former vanishes only in a scenario where the plasma is toroidally symmetric. Therefore, once a finite (m,n) perturbation is superimposed to the equilibrium, the varying magnetic field strength over the toroidal direction leads to a finite damping force (similar to the poloidal damping force on the poloidal flow due to varying toroidal field strength over major radius). This force turns out to be proportional to the toroidal flow, *i.e.* $\left\langle \hat{e}_\phi\cdot\nabla\cdot\overleftrightarrow{\Pi}\right\rangle=-K(r,t)V_\phi$, where $\overleftrightarrow{\Pi}$ is the stress tensor and K(r,t) can be shown to depend on the perturbed magnetic field harmonics and on the collisionality regime [13]. In the plateau regime it is given by

$$K(r,t)=\frac{\pi^{1/2}p_i}{R_0 v_{Ti}}\sum_{m,n}\frac{(\hat{B}_0^\vartheta\hat{b}^{\vartheta(m,n)}+\hat{B}_0^\phi\hat{b}^{\phi(m,n)})}{\hat{B}_0^4}\frac{n^2q}{|m-nq|} \quad (2)$$

where ϑ is a generalized poloidal angle in a straight field line coordinate system, v_{Ti} and p_I are the ion thermal velocity and pressure and the normalisation $\hat{B}^\phi=R_0B^\phi$ and $\hat{B}^\vartheta=rB^\vartheta$ is used. The self similar braking of rotation corresponds to the perfect scenario where K(r,t) is uniform over radius. However, if one considers only the effect of the perturbation with mode number (m,n), K is dominant around the q=m/n. Accounting for mode coupling effects due to non circular plasma cross section, K results distributed over the entire minor radius. In fact, owing to the non circular cross section of the plasma (with given elongation and triangularity) and to the poloidal dependence of the metric coefficients, modes with wavenumbers (m,n) and (m±2 or (m±3,n) are coupled. The (m=0,n=1) magnetic field harmonic that is driven by the (m=2,n=1) mode and elongation turns out to have a toroidal component non vanishing at the magnetic axis. This, in turn, gives rise to a m=0 contribution to Eq. (2) that is dominant near the axis. Therefore, the joint effect of the (m=0,n=1) and (m=2,n=1) contributions results on a globally distributed neoclassical viscous force. In a low collisionality regime, an expression similar to Eq. (2) is derived, that essentially amplifies the effect of this force, in quantitative agreement with the experimental results [13].

4. Conclusions

In conclusion, we have shed some light on the importance that mode coupling effects, generally considered as higher order effects, may have in the description of complex ITER relevant phenomena concerning the stability and dynamics of tokamak fusion plasmas. In particular, we have firstly emphasised on the triggering of the metastable neoclassical tearing mode, a potential hazard for the achievement of high operational plasma beta in ITER-like plasmas. 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, smaller than the threshold width inferred from the $\Delta'(w)$ stability curve, the mode decouples from the coupling drive and acquires it's natural rotation frequency. We have also focused 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. Although toroidal and non-linear mode coupling contribute to a non localised braking of the toroidal rotation around the resonant surfaces inside the plasma, coupling to plasma elongation appears to be essential to explain the experimental observations.

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