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

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1-Introduction

In several Thermonuclear Fusion experiments performed at JET, the peak performance, in terms of neutron yield and plasma stored energy, was observed to deteriorate in coincidence with the onset of fast rotating MHD modes appearing around the time of large sawtooth crashes. These modes with poloidal to toroidal mode number ratio larger than one, m/n>1, are observed at moderate to high _ values in both Elm-free and ELMy H-mode plasmas. In JET ELM-free DT discharges, the growth of n=3 and n=4 modes following a sawtooth crash are clearly associated with saturation of the fusion yield [1]. In recent JET campaigns, the triggering of magnetic islands at different _ values and their effect on confinement were extensively studied in ELMy H-mode plasmas designed to study the onset of Neo-classical Tearing Modes (NTM) [2]. 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 (see Fig. 1). 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. Here we consider the effect of toroidal [3] and non-linear [4] coupling on the marginal stability of NTMs observed in the JET ELMy regime [2]. In those discharges with high _ the conditions are close to the threshold for destabilisation of NTMs. Accordingly we formulate the problem of assessing the conditions for driving a seed island above threshold, by linear or non-linear coupling of modes.

2-Experimental observations and theoretical model

We present first the theory of non-linear coupling of triplets of rotating magnetic islands developed in Ref [4] as an extension of the large R/a Rutherford theory of non-linear tearing modes. This includes the mutual electrodynamic and viscous coupling of a triplet of rotating magnetic islands of different helicities arranged to obtain a "resonant wave-number matching". This mechanism of coupling is different from that arising from the multiplicity of poloidal harmonics generated by metrics of toroidal geometry and involves modes with different toroidal numbers n. Magnetic perturbations are represented by $\delta\vec{B}_{mn} = \nabla\times\left(\Psi_{mn}\vec{b}_{mn}\right) = \delta\vec{B}_{mn}(r).e^{i\left(m\theta-\frac{n}{R}z+\zeta_{mn}\right)} + c.c$ related to the island width $W_{mn} = \left(\frac{\Psi_{mn}}{h_{mn}}\right)^{1/2}$ where $h_r = B_\phi r_{sr} q' / 16Rq^2$. The neo-classical island mechanics for a triplet of “wave-numbers “ k, k', k'' fulfilling a matching condition $k'' = k - k'$ is described by coupled equations for W_{mn} (t) and the rotation frequency. For the cases considered here the mode frequency is practically constant (Fig.1) and its evolution can be ignored, while the width grows non-linearly as: $\frac{dW_p}{dt} = \Gamma_p(W_p, W_q, W_r, \Delta\phi)$. Here (p, q, r)=(1,2,3) label in turn one mode of the coupled triplet. In absence of coupling the p-mode (instantaneous) rate of growth with the neo-classical bootstrap term is:

$\Gamma_p^{(0)}(W_p) = \frac{r_s^2}{\tau_{R,m}}\{-|\Delta'_{0m}| + \beta_\theta[\frac{a_b W_p}{W_p^2 + W_d^2} - \frac{a_{pol_p}}{W_p^3 + W_0^3}] + \mathrm{Re}(\Delta'_{wall_m})\}$ Without loss of generality, we concentrate on a study case, JET discharge No 47285, performed in a campaign of study of NTMs (described in detail in [2]) . The modes observed are presented in Fig.(1). We consider the onset of the (3,2) mode and conjecture the following sequence of events. Initially, the local β_θ for the driven mode (m=3.n=2) and a passive mode (m=4,n=3) is raised by NBI above or marginally above $\beta_{\theta cr} \approx \rho_{i\theta}\left(a_3 a_2^{-3}\varepsilon^{-3/2}\right)^{1/2}\left(L_P L_q^{-1} g\right)^{1/2}|r_s\Delta'|$ which is the critical value for onset of neo-classical tearing instability with $r_s\Delta' < 0$. However, the seed island width of the (3,2) mode at t=22.36 is below the threshold value $W_{seed} < W_{thr}^{(0)}$, therefore $\Gamma_{3,2}^{(0)}(W_{seed}) \le 0$ 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 linear (toroidal) or non-linear coupling produces a perturbation of the rate of growth of the type $\Gamma_{3,2}(W_{3,2}, W_{1,1}, W_{3,2}) = \Gamma_{3,2}^{(0)}(W_p) + \Gamma_{coupl}(W_{3,2}, W_{1,1}, W_{4,3}, \cos\Delta\phi)$, 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 that for the sake of argument we shall assume zero, for maximum interaction. The non-linear coupling term of the triplet combination considered

$\Gamma_{coupl}(W_p, W_q, W, \cos\Delta\phi) = \frac{r_s^2}{\tau_{R,m}} \frac{r_{s1}C}{r_{sp}} \frac{h_r h_q}{h_p} \frac{W_r^2 W_q^2}{W_p^2} \cos\Delta\phi$ and

$$C = \frac{\mu_0}{2}\left\{\left(\frac{r_{s3}}{r_{s1}}\right)^{1-m_1}\left(\frac{r_{s3}}{r_{s2}}\right)^{m_2}\left|\frac{R^2 q^2}{m_1 - n_1 q}\right|_{r_{s3}}\left(\frac{\lambda'}{B_\phi}\right)_{r_{s3}} - \left(\frac{r_{s2}}{r_{s1}}\right)^{1-m_1}\left(\frac{r_{s2}}{r_{s3}}\right)^{m_3}\left|\frac{R^2 q^2}{m_1 - n_1 q}\right|_{r_{s2}}\left(\frac{\lambda'}{B_\phi}\right)_{r_{s2}}\right\}$$

is the coupling coefficient calculated assuming that each non-linear island is equivalent to a driving current sheet located at rational surfaces r_{s1}, r_{s2}, r_{s3} [4] and that global torque balance is maintained. The other symbols are defined as:

$\lambda' \equiv R(J_{0//}/B_\phi)'$, $a_b = a_2\sqrt{\varepsilon}L_P L_q^{-1}$, $a_p(\omega) = a_3(\omega)\left(\rho_{i\theta} L_q L_P^{-1}\right)^2 g(\varepsilon, \nu_{ii})$, $W_d \propto \rho_i^{1/3}$

$W_{thr}^2 \propto \rho_{i\theta}^2 a_3 a_2^{-1}\varepsilon^{-1/2} L_q L_P^{-1} g(\varepsilon, \nu_{ii})$. The mode coupling term is increasing in the region of smaller “seed” island, therefore providing an effective trigger mechanism. If the uncoupled (3,2) mode were neo-classically stable ($\beta_\theta < \beta_{\theta cr}$), then after the mode (1,1) disappears ($W_{1,1} \to 0$), also the (3,2) would decay. On the contrary if mode (3,2) when uncoupled meets the condition ($\beta_\theta \ge \beta_{\theta cr}$, $W_{seed} < W_{thr}^{(0)}$), and after destabilization due to the three-mode coupling it reaches in a short time interval _ a width $W_{3,2} \approx \Gamma_{3,2}\tau \ge W_{thr}^{(0)}$, then even after the (1,1) disappears, the (3,2) keeps growing at a rate $\Gamma_{3,2}^{(0)}$>0 .For a given set of neo-classical parameters, there is a threshold value for the width of the main driving mode (1,1) above which destabilization is irreversible.

In Fig. (1) the modes (1,1) and (4,3) are saturated at a relatively large level (at amplitudes ~2 Gauss and 0.5 Gauss respectively) well before a (3,2) mode is triggered. The neo-classical nature of the perturbations must be related to the regime of the discharge. In Table I and II the main parameters of this shot are reported in the time interval t > 22.s. In Fig. (2) the location of

r_{s1}, r_{s2}, r_{s3} is obtained from the EFIT q profile, and the rotation frequency profile (mapped onto the poloidal angle of the magnetic pick-up coil measurement). Island sizes ($W_{1,1}$, ~0.15m and $W_{4,3}$~0.6m) are estimated from magnetic and T_e profile perturbations.

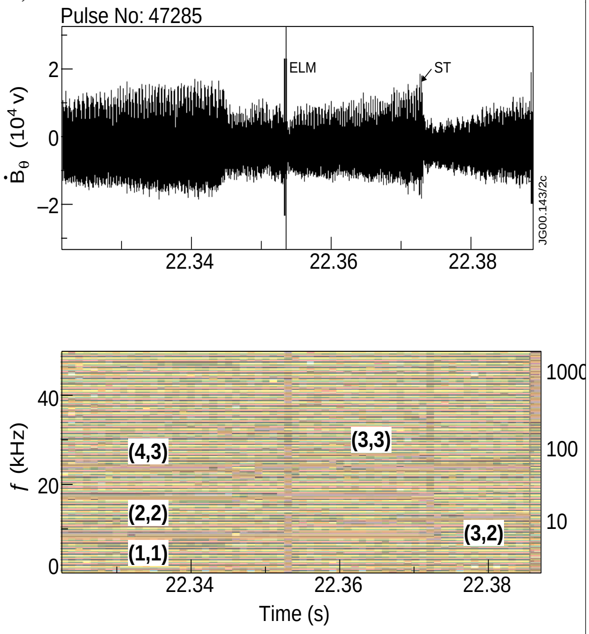

Fig. 1 – a) Magnetic signal measured on the low field side at an angle of 60° above the mid-plane. b) Spectrogram showing the frequency and amplitude of modes observed around a sawtooth crash: the sawtooth precursor (1,1) and its harmonics (2,2) and (3,3), a (4,3) mode unaffected by the sawtooth crash and the onset of a (3,2) mode observed above the noise level at t=22.36 s

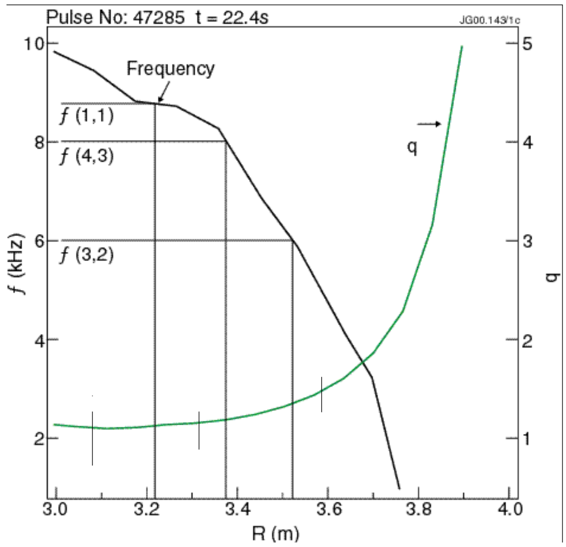

Fig. 2 – Plasma toroidal rotation (charge exchange diagnostic) and q profile (EFIT).

From the data and Fig.(1) it is clear that the (1,1) and (4,3) at t~22.36 modes have grown to sufficiently large amplitudes to drive the (3,2) unstable. In Fig. (3) the condition of trigger of the (3,2) mode is illustrated .

Table I

I_p	B	q_{95}	$T_e(0)$	$n_e(0)$	Z_{eff}	R_0	a	κ	a_2	a_3
1.37MA	1.37 T	3.64	3.8 keV	2.954 $*10^{19}$	2	3.12m	0.94 m	1.7	0.816	.0032

Table II

(m,n)	ρ*	ν*	β_N	L_q	L_p	β_{cr}	β_θ	R_s	W_{po}	W
1,1	.035	0.748	2.825	0.666 m	1.567m		1.98	3.241 m		.144 m
3,2		0.134		0.535 m	0.772m	0.243	3.2	3.523 m	.021 m	
4,3		0.139		0.595m	1.233 m	0.656	5	3.456m	.033 m	.071 m

The same reasoning applies in the case of toroidal coupling of the (3,2) mode with an active (2,2) harmonic of the (1,1) having the amplitude one half of the (1,1). In this case the toroidal coupling term of mode (m,1) with mode (m+1,1) is:

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

and produces a comparable destabilization as shown in the Fig. (4).

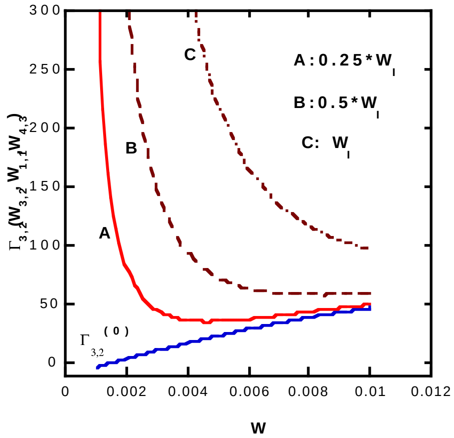

Fig. 3- Growth rates for mode (3,2) with and without non-linear coupling (solid line).) with a seed island W_{seed}< 0.001 is stable and may grow when the driving mode (1,1) reaches $W_{1,1}$>0.035 m, with mode (4,3) at $W_{4,3}$~0.058 m

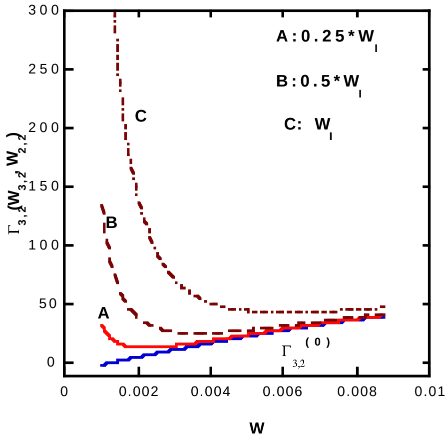

Fig. 4- Growth rates for mode (3,2) with and without non-linear coupling (solid line).) with W_{seed}< 0.001 is stable and may grow when the (2,2) harmonic of the sawtooth pre-cursor, the driving mode, reaches $W_{2,2}$>0.035m.

3-Conclusions

In conclusion we have shown that toroidal or non-linear coupling are effective mechanisms of comparable order to trigger neoclassical tearing modes.

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