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** See annex of F. Romanelli et al, “Overview of JET Results”,*
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ABSTRACT

This work discusses a possible mechanism of spontaneous, triggerless onset of NTMs, observed sometimes on JET, associated with changes in the plasma rotation. The NTM onset threshold is associated with the ion polarisation current: this current can be either stabilizing or destabilizing depending on island rotating in the ion or electron diamagnetic drift direction, and is dependent on to the viscous regimes. Since in the nonlinear stage the magnetic islands necessarily break the ideal tokamak axisymmetry, a Neoclassical Toroidal Viscosity (NTV) appears in the toroidal direction, eventually determining self-consistently the magnetic island propagation speed.

1. ONSET OF NTMS

Experimental observations in tokamaks generally associate the onset of Neoclassical Tearing Modes (NTMs) rotating magnetic islands with (low (m, n) winding numbers to a critical local loss of bootstrap current, marked by $\beta_p > \beta_{cr}$, and to some trigger event exceeding a certain threshold**.** Often the trigger is believed to be a (m = 1,n = 1) sawtooth crash or an ELM although a coupled magnetic perturbation(external or internal) with matching combination of m.n numbers should be more effective. However there is also experimental evidence of spontaneous onset of the instability with subcritical ≤p values and absence of any trigger event. The interpretation of such observations may be provided by considering an important intrinsic *destabilizing mechanism* resulting from the current closure condition $B\nabla_{||} (J_{||}/B) = -\nabla_{\perp}\cdot\mathbf{J}$ that includes the Ion Polarization Current (IPC) [1]. For clarity we refer here to a basic version of Generalized Rurtherford Equation (GRE) for the evolution of the island width w of an (m,n) NTM mode :

$$\frac{4g_1\tau_R}{\pi r_s}\frac{dw}{dt} = r_s\Delta'_0 + \beta_p r_s\sqrt{\frac{r_s}{R_{ax}}}\left|\frac{L_q}{L_p}\right|\left[\frac{a_{bs}w}{w^2+w_d^2} - a_{pol}\left(\frac{r_s}{R_{ax}}\right)\left|\frac{L_q}{L_p}\right|\frac{\bar{\omega}(\bar{\omega}-\omega_T)}{\omega_{*e}^2}\frac{\rho_{i\theta}}{w^2}\right] \qquad (1)$$

where $L_q = q/q'$, $L_p = p/p'$, $w_d \propto \chi_\perp/\chi$, $\varpi = \omega - ck_\theta\,\Phi'/B$ and the steady state frequency ω_T is determined by torque balance, derived elsewhere [2] and described below. The first term in the square brackets is the destabilizing bootstrap current effect and the second is the ion polarization current effect. With the conventions of this paper, for $\bar{\omega} > \omega_T$ the sum of the r.h,s terms is stabilizing for $w < w_{threshold}$ while for $\bar{\omega} > \omega_T$ the r.h.s. is positive and *any* initial perturbation $w \geq 0$ grows. A change of regime of rotation may be the cause of spontaneous onset of the instability. In addition the external control of ω may be used as a tool for NTM avoidance This motivates an open look on experimental cases where the conventional NTMs trigger appears to be missing. A typical example is offered by JET Pulse No: 70069 (Fig.1) where an m = 2, n = 1 NTM appears at 6.65s, in absence of sawteeth or ELMS, when at the q = 2/1 surface the plasma rotation frequency (measured by CXRS) at the q = 2/1 surface has a sudden change to a value $\omega \leq \omega_T \cong \omega_{*pi}$.The figure shows that modelling with eq(1) describes well the mode evolution. Taking another pulse as reference (JET Pulse No: 70684) numerical simulations predict that the external control of plasma rotation near a rational surface, by means of electrodynamic braking of a rotating plasma, could lead to mode growth even in subcritical β_p conditions.

Calculations of i.p.c. role, show the possibility of destabilization or stabilization of the (2,1) mode using or not using the rotation braking effect of the Error Field Control Coils (EFCC).

2. NATURAL PROPAGATION SPEED OF MAGNETIC ISLANDS IN NEOCLASSICAL REGIMES

A central point of this approach is of course an understanding of what really is the natural NTM island propagation speed. In the nonlinear stage the magnetic islands break the ideal tokamak axisymmetry, creating bumps in the modulated confining B field ,that impede the local plasma flow. In the neoclassical collisional regime this appears as a Neoclassical Toroidal Viscosity (NTV) $\langle B_\phi \cdot \nabla \cdot \underline{\underline{\Pi}} \rangle \approx -m_i \, n\mu_t V_\phi \dfrac{\delta B}{\delta_\phi} \neq 0$ that limits self-consistently the magnetic island propagation speed. More precisely the torque applied to the island region is proportional to the expression $\psi_s \; {}'_s \, (\mathrm{W}) = \dfrac{4}{\mathrm{c}} \int_{-\infty}^{\infty} \mathrm{d}x \oint \mathrm{d}\xi \mathrm{J}_{\|} \sin\xi$. Requiring it to vanish is the cardinal mechanical condition to obtain the island propagation speed. By the change of variables from (x, ξ) to the flux-angle variables ($\Psi*$, ξ), using the current closure condition and the parallel momentum balance the expression of the torque can be re-written in the useful form [2]:

$$\tilde{\psi}_s \Delta_s' = \frac{4}{\mathrm{B}^2} \; \frac{\mathrm{L_s}}{\mathrm{k_\theta R \psi_s}} \int_1^\infty \mathrm{d}\Psi^* \int_{\xi_-}^{\xi_+} \mathrm{d}\xi \mathrm{e_r} \cdot \nabla \times \left(\frac{f \langle B \cdot \nabla \cdot \Pi_{//a} \rangle}{\langle \nabla_{//} B \rangle} B \right) \tag{2}$$

where averaging is performed over the is and region and <f> = O(1) and $\xi_\pm$correspond to the island's contours turning points . It is apparent that for an arbitrary island the torque vanishes if the parallel neoclassical viscous stress vanishes [3]. From a basic relation between the parallel neoclassical force $\langle \mathbf{B} \cdot \nabla \cdot \underline{\underline{\Pi}}_{\|a} \rangle$ generalized to non-axisymmetric cases [3-7] (with the CGL form of the stress tensor $\underline{\underline{\Pi}}$ for species a = e,i), and the parallel particles and heat flows and the relation of these with the thermodynamic forces, an *equation* for the island "natural" (normalized) frequency $\omega_\mathrm{N} = (\omega - \omega_\mathrm{E})/\omega_\mathrm{E}$ can be obtained [2] for all collisional regimes spanned by a parameter $s = \omega_\mathrm{E}/(v_\mathrm{i}/\varepsilon)$, i.e. $s < 1 < 1/v^*$. and $s >> 1$:

$$\bar{\omega}_N \omega_E = -(\omega_{*pi} + g_i(\bar{\omega}_N, s)\omega_{*Ti})(1 + s^2) \left[1 + \frac{(\omega_{*pi} + g_i(\bar{\omega}_N, s)\omega_{*Ti})}{(\omega_{*pe} + g_e(\bar{\omega}_N, s)\omega_{*Te})} s^2 \right]^{-1} \tag{3}$$

where $g_a(\bar{\omega}_N, s) = \left(\dfrac{\mu_{2a}}{\mu_{1a}} \right) \dfrac{\bar{\omega}_N^2 s^2 + (\mu_{1a}/\lambda_{1a})G}{\bar{\omega}_N^2 s^2 + (\mu_{2a}/\lambda_{2a})G}, \; G \propto \left(\dfrac{w}{r_s} \right)^2$ are obtaines using the coefficients $\lambda.\mu$ of Ref.[6]. Across the s range in absence of a bulk plasma parallel velocity the island frequency varies from the electron diamagnetic frequency (here<0) to the ion one (>0), as shown in Fig. (3). In absence of (steady) driven parallel flow the ion polarization current effect vanishes as the island frequency reaches its “natural“ value, from its initial (arbitrary) value. But the transition may proceed with a change of sign and therefore a destabilizing effect. It is however clearly possible to conceive an NTM avoidance strategy by imposing a suitable bulk parallel speed. The JET experimental cases discussed in this paper document both the spontaneous onset of NTM’s associated with a change of sign of the rotation (with respect to an initial reference value) and the possibility of using externally applied torque through electrodynamic braking, to achieve the same destabilization or test for NTM avoidance strategies by control of rotation.

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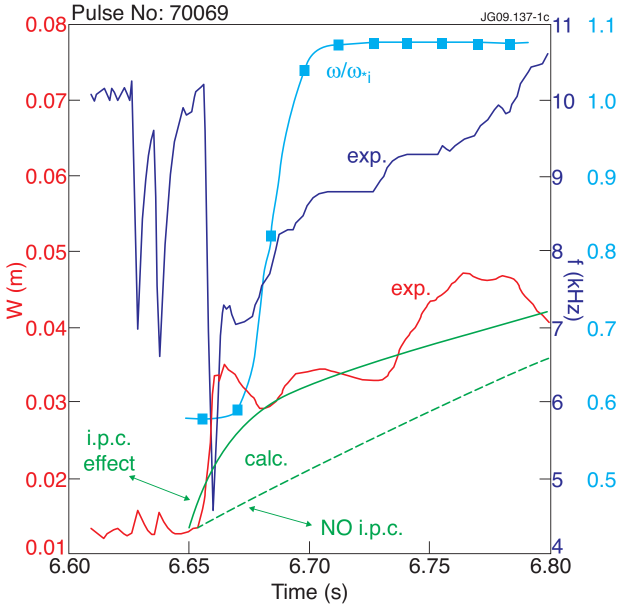

Figure 1: Seedless NTM destabilization by i.p.c when $\omega \leq \omega_T \cong E\ \omega_{*pi}$.

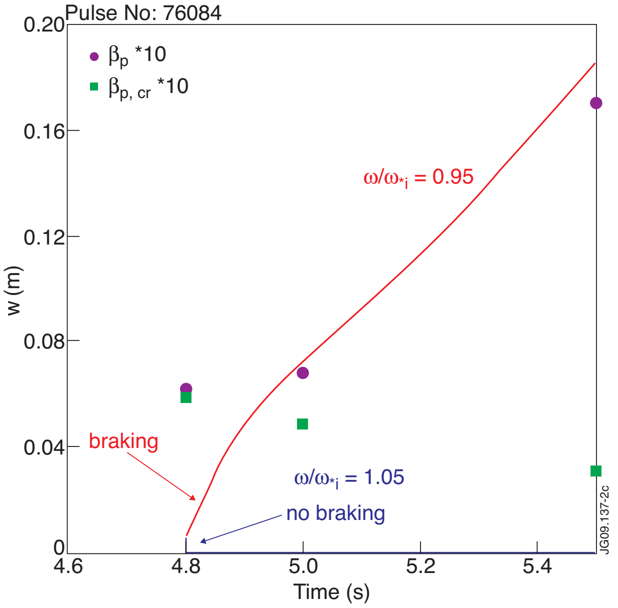

Figure 2: Rotation control for i.p.c based NTM onset for $\omega \leq \omega_T \cong \omega_{*pi}$ *or avoidance for* $\omega > \omega_{*pi}$.

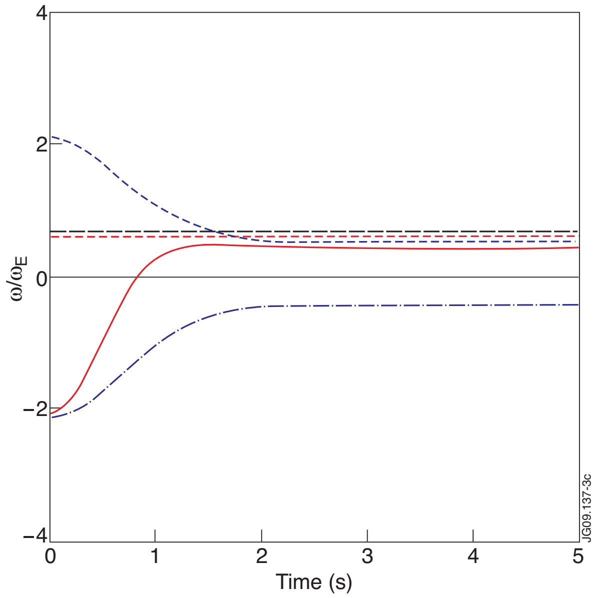

Figure 3: The island frequency (full thick line) changes from $\omega_{*pe}+g_e\ \omega_{*Te}$ *(dash–dot line) to* $\omega_{*pi}+gi\ \omega_{*Ti}$ *(dashed line) as s spans the collisional regimes. The thin dashed and dotted lines are* ω_{*pi} $(=-\ \omega_{*pe})$*and* ω_{*Ti}.