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Unlocking static coupled magnetic islands in the presence of resistive wall effects and external resonant magnetic fields

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I - Introduction

Resistive tearing modes are widely recognised as being a cause for the performance limitations, stability and confinement of many tokamak discharges. The topology of the nested toroidal magnetic surfaces of the tokamak equilibrium is torn, and field lines reconnect into a configuration with islands. The non-linear time evolution of a tearing mode (island size and mode frequency) is modified when the mode is coupled to other modes [1] or when it interacts with external structures or resonant magnetic perturbations such as, respectively, the tokamaks' resistive wall [1] and resonant external magnetic fields [2].

Error-field driven tearing modes, if sufficient virulent, may lead to the plasma disruption. The mode is strongly destabilised at a sufficiently damped frequency, the resistive wall contributing also to this damping [3]. One way to avoid this destabilisation is to impart some rotation to the mode, while having its' width under control (without reducing it) by contrasting the error-field.

In this work, the unlocking of static resistive tearing modes (both isolated and coupled) by slowly rotating external magnetic perturbations is discussed in terms of a competition between the accelerating torque imparted by the external perturbation and the braking torque due to the interaction of the mode with the resistive wall. Unlocking thresholds for the amplitude of the equivalent external current are examined.

II – Numerical model for island unlocking

In this work we consider the regime where the poloidal rotation is efficiently damped by the poloidal projection of the parallel viscous stress, which dominates the other driving forces. Consequently, poloidal rotation is neglected and the role of viscosity is essentially that

[&] presently at Istituto di Fisica del Plasma CNR, Milan, Italy of allowing relative motion (toroidally) of the island with the ambient plasma. We also assume that the error-field is cancelled by the (DC) component of the external field and that during the unlocking process the existing islands don't change significantly their width (controlled for instance by rf-wave driven current deposition). This allows us to neglect inertial effects and study the competition between wall braking torques and external current driven mode acceleration (in a non negligible viscosity scenario, viscosity would provide an additional accelerating torque due to the finite plasma velocity [3]).

Under these conditions, the time evolution equation for the frequency of a (m,n) mode is given by

$$\frac{d\omega}{dt} = \frac{n}{I_\phi} \cdot \left(\frac{2\pi^2 R}{\mu_0} \cdot r_s n \cdot \mathrm{Im}(\Delta') \cdot k^2 W^4\right) \qquad (1)$$

with the stability parameter Δ' (logarithmic jump in the radial derivative of the flux function across the resonance), with resistive wall and external current boundary conditions, given by

$$\Delta' = \Delta'_0 - \frac{2m}{r_s}\left(\frac{r_s}{d}\right)^{2m} \frac{(\omega\tau_{wm})^2 + i(\omega\tau_{wm})}{1+(\omega\tau_{wm})^2} + C_{cp}\frac{k_{cp}W_{cp}^2}{kW^2} \cdot e^{i(\phi_{cp}-\phi)} + C_E \frac{I_E}{kW^2} \cdot e^{i(\phi_E-\phi)} \qquad (2)$$

Here $I_\phi = C_\phi \cdot n_e(r_s) \cdot W$ is the effective toroidal momentum of inertia of the amount of plasma (density n_e) associated with an island of separatrix width (W) and helicity (m,n), $\tau_w = m \cdot \tau_{wm}$ is the resistive skin time of the resistive vessel, C_ϕ is a geometrical constant, $k \equiv \frac{\psi_s}{W^2}$ and ψ_s is the reconnected magnetic flux at the rational surface. The constant C_{cp} measures the strength of the interaction between the mode (m,n) and the one with which it couples (phase ϕ_{cp} and width W_{cp}) and C_E measures the strength of the interaction between the mode and the external resonant magnetic perturbation ($\frac{d\phi}{dt} = \omega$ and $\frac{d\phi_E}{dt} = \omega_E$, where ω_E is the frequency of the externally imposed field) [4].

III – Thresholds for single and coupled islands

Labelling the inner mode (lower m/n) as *mode 1*, and in the absence of coupling and inertial effects ($dI_\phi/dt=0$), the threshold for the external current, above which the mode frequency will equal the external field frequency in stationary conditions, corresponds to a scenario where the rotating tearing mode frequency (ω_1) is equal to that of the external field (ω_E) and the phase difference $\Delta\phi_E \cong \frac{\pi}{2}$. If, at $\Delta\phi_E \cong \frac{\pi}{2}$, we have $\omega_1 < \omega_E$, then $\Delta\phi_E$ will keep on increasing and the mode is unable to lock to the external field. The threshold current $I_{E,thresh}$ is thus given by

$$I_{E,thresh} = \frac{1}{C_E}\frac{2m_1}{r_{s1}}\left(\frac{r_{s1}}{d}\right)^{2m_1}\frac{\omega_E\tau_{w1}}{1+(\omega_E\tau_{w1})^2}\cdot k_1 W_1^2 \tag{3}$$

and, for such a current, the time evolution of the mode frequency is given by

$$\frac{d\omega_1}{dt} = C_0\frac{W_1^3}{n_e(r_s)}\left(-\frac{\omega_1\tau_{w1}}{1+(\omega_1\tau_{w1})^2}+\frac{\omega_E\tau_{w1}}{1+(\omega_E\tau_{w1})^2}\cdot\sin(\Delta\phi_E)\right) \tag{4}$$

We can thus determine numerically the maximum error field frequency above which the threshold current is not valid and this can be seen in Figure 1. Due to the non-linear wall response to magnetic perturbations, an upper limit in this maximum frequency appears to be observed at $\omega \approx 1/\tau_w$ (the numerical simulations were performed having as reference the plasma profiles and machine parameters of the FTU tokamak [5] and a (2,1) mode).

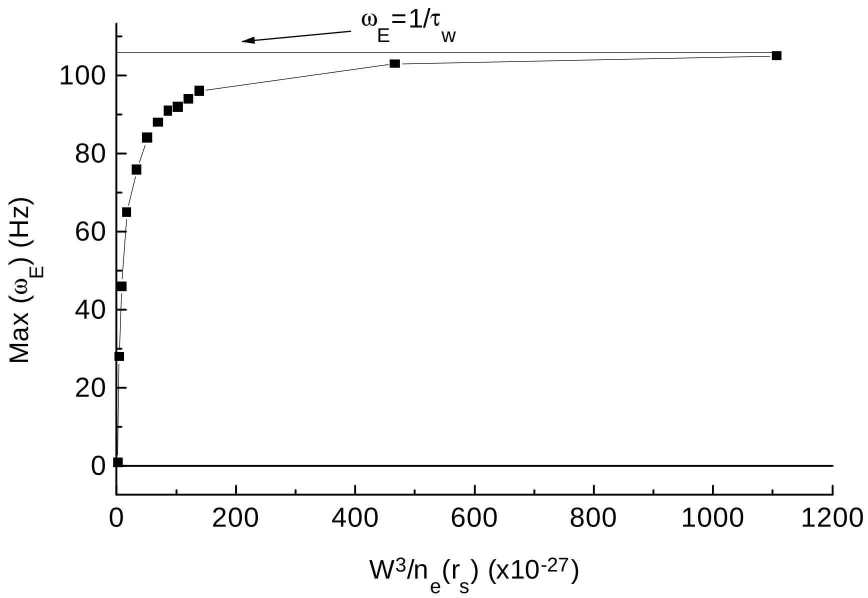

Figure 1 – Maximum error-field frequency above which the threshold condition fails. An upper limit of the order of the inverse of the resistive time of the vessel for the mode is observed.

When the mode resonant with the external field is coupled to another existing mode, the time response of the inner mode (a (2,1) mode) to the external field perturbation is expected to be reduced due to the coupling to the outer mode (a (3,1) is considered). In fact, a larger "effective inertia of the (2,1) mode" which depends on the ratio between the widths of both islands is observed, resulting on a larger external current amplitude necessary to unlock both modes from the wall (see Figure 2).

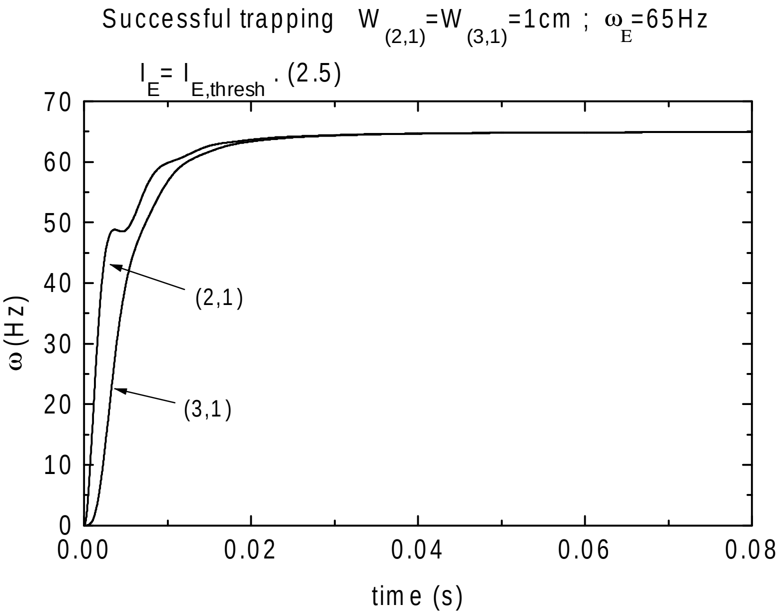

Figure 2 - Successful trapping of toroidally coupled (2,1) and (3,1) islands to a rotating external-field, resonant with the (2,1) mode, with ω_E=65 Hz. An additional 150% of current is needed for a ratio $W_1/W_2=1$

IV – Conclusions

In this paper, a discussion on the external current thresholds necessary for the unlocking of non-linear tearing modes alone an coupled toroidally in the presence of the resistive tokamak wall was presented. Besides the competition between the accelerating external field torque and the wall braking torque, finite island inertia is shown to play an important role, specially when two modes are coupled, resulting on a net increase of the inertia of the island resonant with the external field.

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