

Evaluation of Two-Fluid effects on Double-Tearing Mode stability

P. Maget, G.T.A. Huysmans, H. Lütjens¹, M. Ottaviani, Ph. Moreau, J.-L. Ségui

Association Euratom-CEA, CEA/DSM/IRFM, Centre de Cadarache, 13108

S^t-Paul-lez-Durance, France

¹ Centre de Physique Théorique (Ecole Polytechnique), 91128 Palaiseau, France

Introduction

The stability of ($m = 2, n = 1$) Tearing or Double-Tearing mode in Tore Supra hollow current profile discharges is known to be marginal [1], in agreement with one fluid MHD description where the major stabilizing contribution comes from toroidal curvature [2], and neglecting heat transport. However, finite heat transport plays against the favourable S -dependence of the curvature term [4], due to the loss of the favourable role of the Lundquist number $S = \tau_R/\tau_A$ with τ_R and τ_A the resistive and Alfvén times respectively. Also, finite rotation of the MHD mode in the plasma frame is expected to weaken dramatically the curvature term [5]. We investigate in the present work the impact of finite transport and of electron diamagnetic effect on the stability of a typical Tore Supra non-inductive equilibrium with hollow current profile, in both the linear and non-linear regimes.

Linear MHD stability and the issue of transport and diamagnetic effects

The linear MHD stability of a typical equilibrium (fig. 1) is first calculated using the standard one-fluid MHD model, without transport, as implemented in the CASTOR code [3]. Due to double-resonant $q = 2$ surface, two branches are identified, corresponding to mode structures localized on the inner or outer surfaces. At the level of experimental resistivity, the $n = 1$ resistive mode localized at the outer resonant surface is (marginally) stable, while the one localized on the inner surface is still unstable (fig. 2). This result is consistent with the evaluation of toroidal curvature effect at marginal stability. The cylindrical $r\Delta'$ is found to be ≈ 12 , and is significantly compensated by the curvature correction $r\Delta'_c = 1.54 [x_s^4 (nsS)^2 / (1 + 2q^2)]^{1/6} D_R^{5/6}$ [2], which is ~ 6 taking S at the outer $q=2$ surface, and ~ 12 with the $S(0)$. This satisfactory result is however invalid when the growth time is slow enough to allow heat transport to equilibrate the pressure along field lines, as expected for tearing modes. The critical value to be compared to $r\Delta'$ is then independent from the Lundquist number, and is much lower than $r\Delta'_c$ for moderate performance plasmas: $r\Delta'_\chi = \sqrt{2}\pi^{3/2} D_R / (W_\chi/r) \approx 1.1$, with $W_\chi/r = 2\sqrt{2} (\chi_\perp/\chi_\parallel)^{1/4} / \sqrt{rns/R}$ and $\chi_\parallel/\chi_\perp = 10^8$ with χ_\perp and χ_\parallel respectively the perpendicular and parallel heat diffusivities [4]. This evaluation predicts an unstable tearing mode on the outer $q = 2$ surface. If we now turn to a model that includes electron diamagnetic effect (but not heat transport), such as the

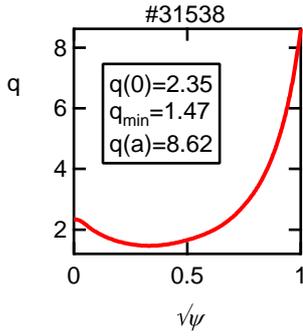


Figure 1: Typical equilibrium.

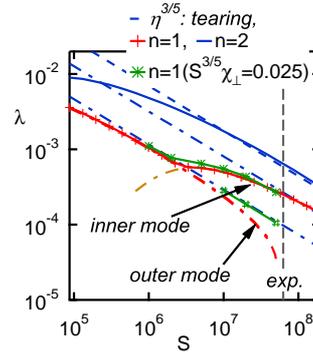


Figure 2: Linear stability with and w/o transport.

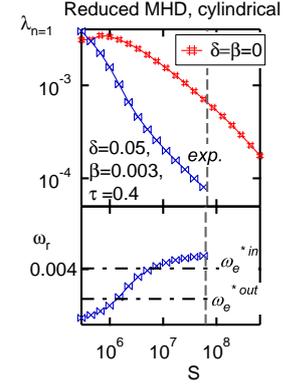


Figure 3: Linear stability in 4-fields model.

Drift-Tearing model, we find that for experimental conditions on Tore Supra, toroidal geometry does not bring significant stabilisation to the (2,1) tearing mode [5]. The reason is that the high Lundquist number does not play a significant role in the parameter regime of interest, where the threshold to be exceeded is: $r\Delta'_{DT} \approx 0.35 (D_R\beta)^{1/2} r/\rho_s \approx 0.3$. Again, one expect an unstable (2,1) mode to growth on the outer resonant surface. But Drift-Tearing modes have complex non-linear features, due to the pressure response in different collisional regimes, and they exhibit multiple non-linear states, among which metastable states [7, 8]. As a consequence, the linear stability analysis is insufficient to predict the real impact of the mode. In Tore Supra experiments, both stable and unstable cases are observed (they correspond respectively to the so-called Gigajoule experiment case and to the transition to MHD regime case [9]). The particular discharge (#31538) that is taken as a reference in this work belongs to the first category, with a stationary (3,2) mode and no sign of MHD activity at $q = 2$.

The impact of finite heat diffusivity on the $n = 1$ mode, investigated using the XTOR code [10], is found to be mildly destabilizing for the inner resonant mode, but more importantly the outer mode is not longer linearly stable at experimental resistivity, as could be expected from the corrected stability threshold (fig. 2). Note that in varying the Lundquist number, we take $\tau_{MHD}/\tau_E \propto S^{3/5}\chi_{\perp} \approx (S^{3/5}\chi_{\perp})^{exp.}$, and $\chi_{\parallel}/\chi_{\perp} = 10^8$.

We now consider diamagnetic effects coming from electron pressure gradient. We first consider a four-field reduced MHD formulation of the drift-tearing model, in cylindrical geometry, described in [6]. The input coefficients are $\beta = 3 \times 10^{-3}$, $\delta = 5 \times 10^{-2}$, and $\tau = T_i/T_e = 0.4$. We find that the mode frequency moves above the diamagnetic frequency when increasing the Lundquist number, and that the growth rate is about one order of magnitude lower compared to the same calculation with $\beta = \delta = 0$ (fig. 3). At the experimental resistivity level, diamagnetic

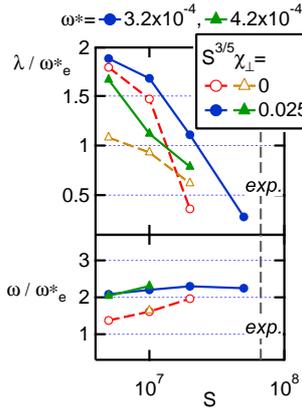


Figure 4: Electron diamagnetic effects with XTOR.

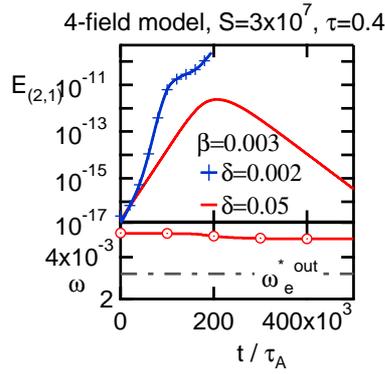


Figure 5: Non-linear behaviour (4-field model).

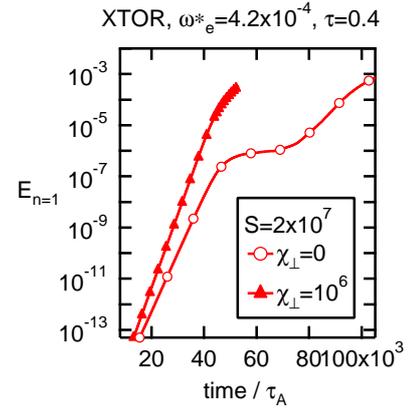


Figure 6: Non-linear evolution including ω_e^* (XTOR).

effects brings the mode close to stability (the radial structure becomes oscillating and numerically challenging to resolve).

In order to investigate electron diamagnetic effects in toroidal geometry, we use XTOR code, where the electron diamagnetic contribution is modelled by an additional term in Ohm's law: $\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} - \nabla_{\parallel} p_e / (en)$. In the linear regime, it is found that heat transport increases both the growth rate and frequency of the mode (fig. 4). Even in this case however, the Drift-Tearing ordering $\lambda = \gamma \tau_A < \omega_e^*$ is expected to be fulfilled at the experimental S ($\omega_e^* \sim 3 \times 10^{-4}$).

Non-linear aspects

In the non-linear regime, the standard MHD model including transport predicts that our magnetic equilibrium should experience first a full reconnection of the most unstable ($n=2$) mode, and then of the $n=1$ mode, as can be expected from fig. 2. This situation is indeed encountered experimentally, with a double-crash leading then to the so-called MHD regime, characterized by a large $n=1$ mode (fig. 7) [1]. However, the $n=1$ mode is stable in the experiment considered, and this cannot be explained when including finite heat transport. Conversely, electron diamagnetic effect is a possible mechanism for such a stabilisation.

With the Drift-Tearing model in cylindrical geometry and S such that $\lambda / \omega_{*e} \sim 3 \times 10^{-2}$, the (2,1) Double-Tearing Mode grows to a maximum and then decays (fig. 5). At their maximum, the inner and outer islands measure $(w/a)_{in} = 0.0009$ and $(w/a)_{out} = 0.0024$, and the mode frequency remains approximately constant along the simulation, significantly above the electron diamagnetic frequency at the two $q = 2$ surfaces. Such a behaviour is reported in [7], where it is demonstrated that it originates from quasi-linear stabilisation by parallel transport, which rebuilds the electron diamagnetic rotation.

Simulations have been run in the non-linear regime with XTOR, thus covering possible effects coming from toroidal geometry and heat transport. At $S = 2 \times 10^7$ and $\chi_{\perp} = 0$, we have $\lambda / \omega_{*e} \sim 0.8$, and the mode experiences a first saturation phase dominated by the inner resonance, but the outer resonant mode has still a large saturated state (fig. 6). When including transport, the outer mode dominates. We are however marginally in the Drift-Tearing domain, in particular with transport, and investigations at higher S or ω_{*e} are required to approach the right non-linear regime.

Discussion

We have investigated in the present work possible mechanisms that could explain the complex stability behaviour of the $n=1$ DTM in Tore Supra experiments. While this mode is stable in Gigajoule experiments, it produces large pressure collapse in other similar conditions. This suggests a bifurcating behaviour that cannot be obtained with the standard MHD model, while it is typical of Drift-Tearing models. First, we show that the Drift-Tearing ordering $\lambda < \omega_{*e}^*$ is verified in the experiment, even when anomalous transport is considered. Then, using a reduced MHD 4-field model, we find a decay of the DTM in the non-linear regime. Such a behaviour may however disappear when a small seed is provided to the island, as found in [7, 8]. Finally, simulations including electron diamagnetic frequency and heat transport in toroidal geometry with XTOR have been performed. Simulations up to $S = 2 \times 10^7$ are still marginally in the Drift-Tearing regime, and ω_{*e}^* should be increased artificially to approach the experimental conditions.

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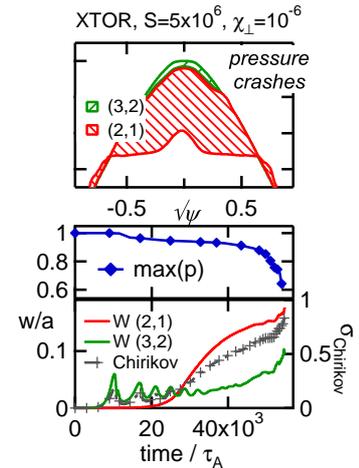


Figure 7: Transition to MHD regime with standard MHD model.