Dynamics of a Double-Tearing Mode with diamagnetic and neoclassical physics in Tore Supra

P. Maget, H. Lütjens[1], J.F. Luciani[1], O. Février, X. Garbet, J.L. Ségui and Tore Supra team

CEA, IRFM, F-13108 Saint Paul-lez-Durance, France.

[1]*Centre de Physique Théorique, Ecole Polytechnique, CNRS, France.*

Summary Tearing modes associated to hollow current profiles are prone to grow in moderate performance plasmas, and often constrain the realization of non-inductive discharges in the Tore Supra tokamak, where long pulse duration are performed using Lower Hybrid waves for providing most of the plasma current. The prediction of MHD boundaries in such scenarios is complicated by the importance of diamagnetic effects, combined with curvature stabilization, which determine the stability of these modes. We show that diamagnetic effects, as well as neoclassical forces, are playing a key role in the linear and nonlinear regimes of Double-Tearing Modes on $q = 5/3$ and $q = 2$ in these experimental conditions.

Experimental observations The experiment of interest is characterized by a toroidal magnetic field $B = 3.4T$, a plasma current $I_p = 660kA$, a Lower Hybrid wave (LH) power $P_{LH} = 5MW$ that provides about 66% of the total plasma current. In this discharge, a Double-Tearing Mode is diagnosed using Electron Cyclotron Emission (ECE) at $t = 25.5s$ (fig. 1). Two different phases can be distinguished. The first one lasts about 3ms, and is slow enough to allow the identification of the mode frequency and structure (fig. 2). The second one is extremely fast (about $80\mu s$), and leads to a temperature crash that flattens the electron temperature from the core to outside the inversion radius, although the temperature at the very core decays on a slightly slower time scale (fig. 1).

This observation has been analyzed with the two-fluid nonlinear MHD code XTOR-2F [1], on the basis of a CRONOS integrated simulation. Temperature and densities are taken from experimental measurements, and the LH current drive is determined using Hard X-ray tomography inversion, constrained in amplitude by the inductive flux consumption. The superposition of the mode structure determined by the fluctuations of electron temperature with the safety factor profile q given by the integrated simulation provides strong evidence that the initial DTM develops on the $q = 5/3$ surface, the odd parity of the mode being given by the opposite sign of the perturbation on both sides of the magnetic axis (fig. 2). The exact shape of the q-profile inside $q = 5/3$ cannot however be constrained by these experimental measurements, and we find some indications in our study that the equilibrium computed by CRONOS is not the experimental one in the very core region.

Numerical simulations The experimental situation has been modelled using the non lin-

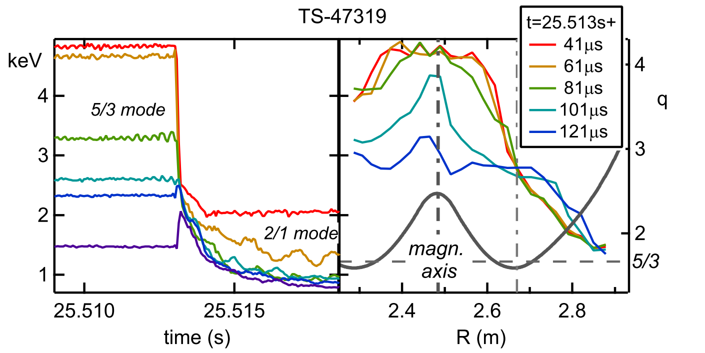

Figure 1: *Left: Electron temperature dynamics. Right: Profiles of $T_e(R)$ at the crash, and safety factor profile.*

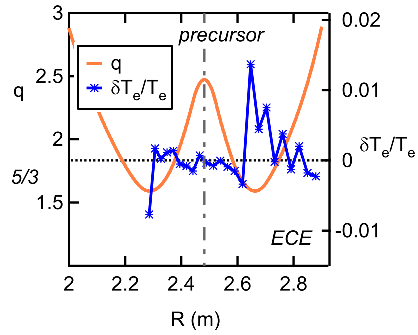

Figure 2: *Precursor of the crash (from ECE).*

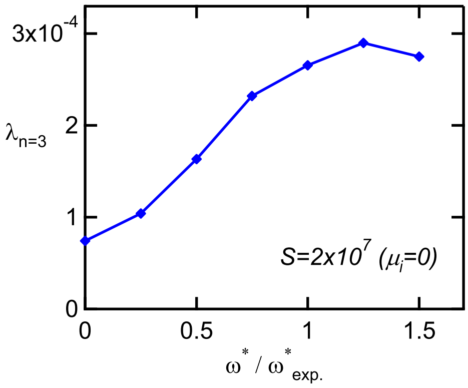

Figure 3: *Growth rate of $n = 3$ mode as a function of ω^*/ω^*_{exp}.*

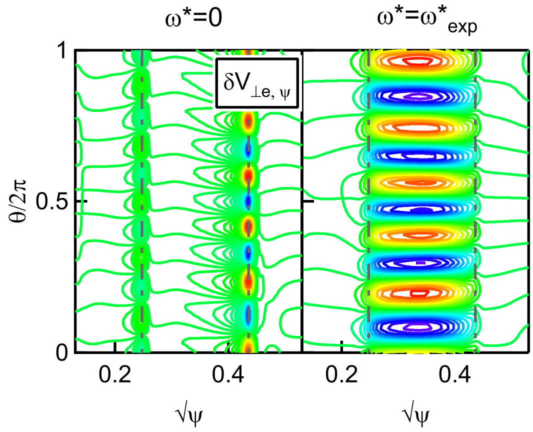

Figure 4: *Perturbed perpendicular electron flow, with and without ω^*.*

ear MHD code XTOR-2F [1], which solves the two fluid MHD equations in a tore, including anisotropic heat diffusivity, as well as neoclassical physics [2].

Linear regime The linear regime evidences two main effects: a destabilization by (electron) diamagnetic rotation [3] (fig. 3), combined with a destabilization by ion neoclassical friction (fig. 5). The first effect can be related with the perpendicular electron flow that better connect the two resonances through ω^*, thus facilitating the reconnection process (fig. 4). The second effect is due to the widening of the perturbed pressure by neoclassical friction (measured by $\alpha_\mu = (\mu_i/\eta)/(\mu_i/\eta)_{exp}$), that reduces the stabilizing effect of curvature [4].

Competition between $n = 1$ and $n = 3$ modes The combined effect of diamagnetic rotations and neoclassical friction strongly modifies the competition between $n = 1$ and $n = 3$ modes, that are both unstable (fig. 7). In the single fluid MHD model, the $n = 1$ mode dominates, and diamagnetic destabilization is required for recovering the domination of the $n = 3$ instability, the saturation level being further increased by neoclassical ion friction.

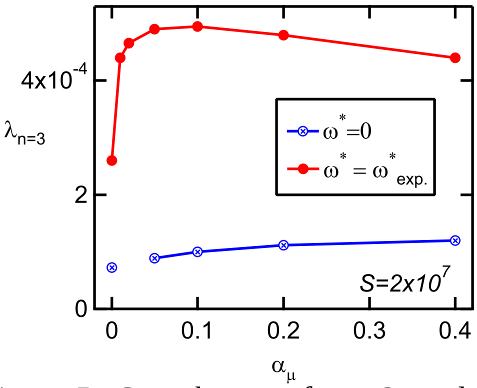

Figure 5: *Growth rate of* $n = 3$ *mode as a function of the ion neoclassical friction coefficient.*

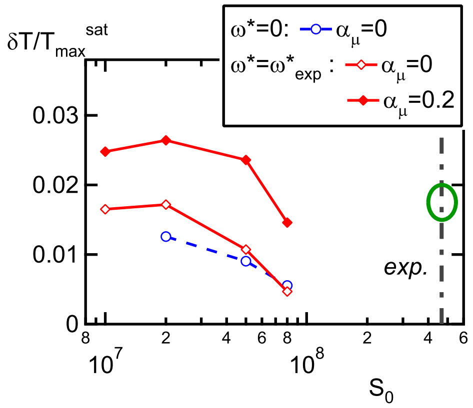

Figure 6: *Relative temperature perturbation at (5,3) DTM saturation as a function of the Lundquist number at plasma center.*

Quasilinear saturation of the $n = 3$ ***DTM: resistivity effect*** Numerical computations being performed at a resistivity larger than the experimental one, we investigate the dependence of the saturation level of the (5,3) DTM on the Lundquist number at plasma center $S_0 = \tau_R/\tau_A$ (fig. 6). We find that, although we are in the nonlinear regime, the Lundquist number impacts the mode saturation (in contrast with standard Rutherford model), as already found for the single tearing [5], where this was related to a reminiscent curvature effect [6]. This leads to a decay of the saturation level well below the observation at increasing S_0, even when the ion neoclassical friction is covered (note that the bootstrap current perturbation does not affect significantly the saturation level due to the small perturbation). The investigation of alternative q-profiles shows in fact that a stronger reversal in the negative shear region can provide a larger saturation, consistent with the experimental one [7].

Conclusion In this work, a close comparison between experimental measurements and non-linear MHD simulations evidences the manifestation of bi-fluid and neoclassical effects on a Double Tearing Mode observed in Tore Supra. These extensions of the standard single fluid MHD model modify both the linear and nonlinear regimes. In the regime considered, the linear growth rate is increased by diamagnetic rotation as well as by the ion neoclassical friction. In the nonlinear phase, ion neoclassical friction is the main effect leading to a larger saturation. However, in the competition between the $n = 3$ and $n = 1$ modes, the faster growth given to the $n = 3$ DTM by diamagnetic rotation explains why this instability is observed instead of the $n = 1$ mode. Regarding the fast crash, not recovered in our simulations, it could result from the growth of Resistive Interchange Modes that are unstable in the negative magnetic shear region, from geometric deformation of the 5/3 island [8] (these two mechanisms require computing

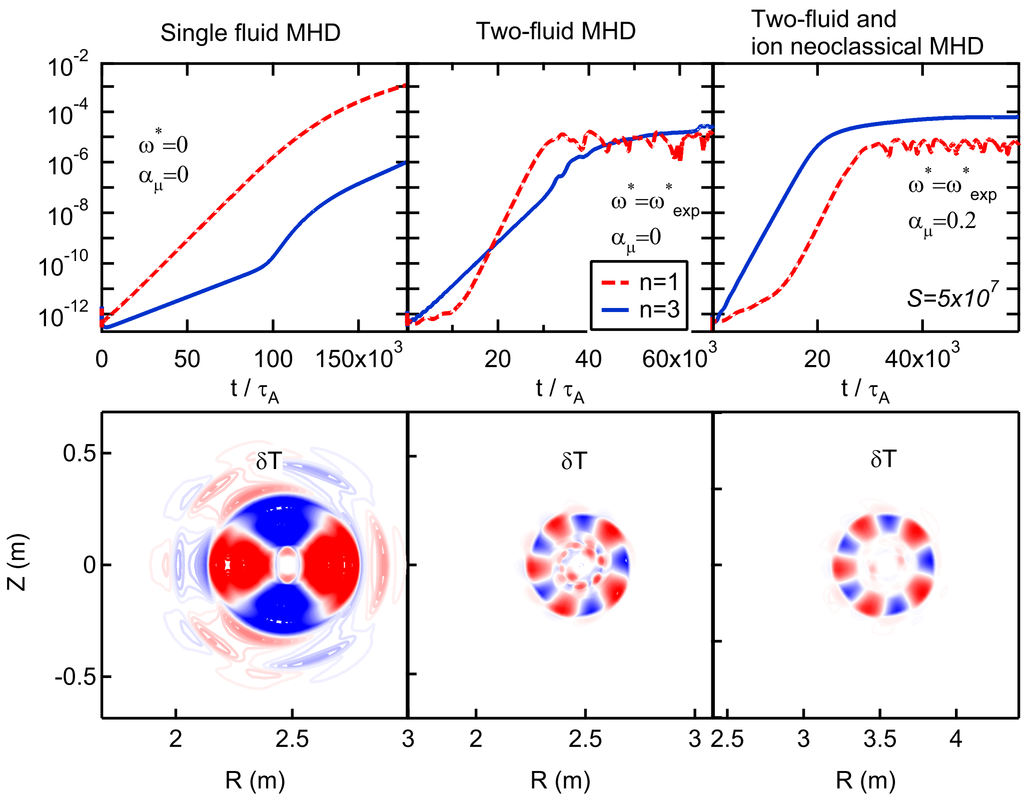

Figure 7: *Nonlinear evolution of magnetic energies for $n = 1$ and $n = 3$ modes (top) and 2D contour of δT at the end of the simulations (bottom).*

high toroidal mode numbers), or from missing physics like electron inertia.

Aknowledgements The authors thank J.-F. Artaud for providing the CRONOS results. This work was carried out within the framework the European Fusion Development Agreement (EFDA) and the French Research Federation for Fusion Studies (FR-FCM), using HPC resources from GENCI (project 056348) and from Aix-Marseille Université project Equip@Meso (ANR-10-EQPX-29-01) of the program "Investissements d'Avenir" supervised by the Agence Nationale pour la Recherche (project 13b010). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] H. Lütjens and J.F. Luciani, Journal of Computational Physics 229 (2010) 8130 .
[2] N. Mellet et al., Nuclear Fusion 53 (2013) 043022.
[3] D. Meshcheriakov et al., Physics of Plasmas 19 (2012) 092509.
[4] P. Maget et al., Physics of Plasmas 20 (2013) 112504.
[5] D. Meshcheriakov et al., Physics of Plasmas 21 (2014) 012516.
[6] A.H. Glasser, J.M. Greene and J.L. Johnson, Physics of Fluids 18 (1975) 875.
[7] P. Maget et al., Physics of Plasmas 21 (2014) 062504.
[8] Y. Ishii et al., Phys. Rev. Lett., 89 (2002) 205002.