Evidence of bi-fluid destabilization of a double tearing mode in Tore Supra

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Summary Tearing modes associated to hollow current profiles are prone to grow in moderate performance plasmas, and often constrain the realisation of non inductive discharges in Tore Supra [1]. 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 and depends on details of the pressure and density profiles [2]. The weak MHD stability is illustrated here by the growth of a $(5,3)$ Double-Tearing Mode (DTM) after the switch-off of 3MW of ICRH, and a moderate change of equilibrium profiles in the core, while 5MW of LH maintains the major part of plasma current and electron heat source. This observation has been analyzed with the two-fluid non linear MHD code XTOR-2F [3], on the basis of a CRONOS integrated simulation [4]. It appears that diamagnetic effects [2], as well as neoclassical friction [5], are playing a key role in the linear and non linear regimes in these conditions, and are required for explaining the observed pressure crash driven by the $(5,3)$ DTM.

Experimental observations In the discharge of interest, a Double-Tearing Mode is diagnosed using Electron Cyclotron Emission (ECE) at $t = 25.5s$, leading to a temperature crash after a short linear growth. Following this crash, a slowly growing mode sets in, whose poloidal (m) and toroidal (n) mode numbers can be identified with an array of Mirnov coils as $(m = 2, n = 1)$, leading to the so-called MHD regime [6] (fig. 1). The characteristic of these modes can be determined more precisely using integrated simulations of the plasma equilibrium evolution with the CRONOS suite of codes [4]. 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. The consistency of the equilibrium is confirmed by the good agreement between the (2,1) mode structure at $t = 25.6s$ and the q-profile at that time, although some freedom exists for the q-profile shape in the very central part of the plasma (fig. 2).

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

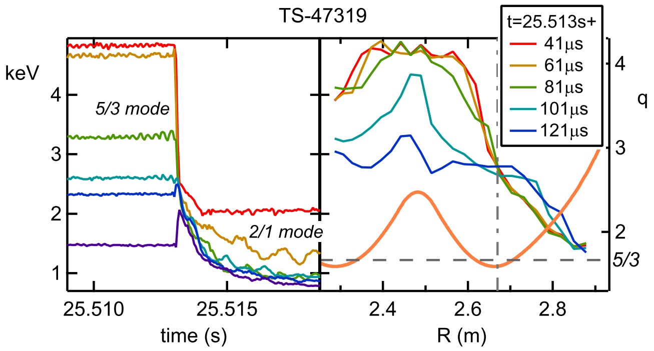

Figure 1: *Left: Electron temperature at varius radius as a function of time. Right: Profiles of $T_e(R)$ at the crash, and safety factor profile from CRONOS (right scale).*

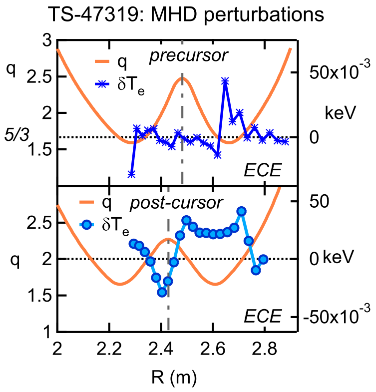

Figure 2: *Precursor (at $t = 25.51s$) and postcursor (at $t = 25.6s$) of the crash.*

ear MHD code XTOR-2F [3], which solves the two fluid MHD equations in a tore, including anisotropic heat diffusivity, as well as neoclassical physics with the friction coefficient μ_i forcing the poloidal ion flow to its neoclassical value [5]. Several modifications of the original safety factor profile have been considered close to the magnetic axis (fig. 3). Indeed, the relaxed state of the DTM is usually well described by the full reconnection model in the absence of diamagnetic physics [7], and requires that the helical flux $\psi^* = \int d\psi(1 - q/q_{res})$ has a positive maximum for leading to the full crash that is observed [8]. This suggests taking a flatter q-profile. On the other hand, it has been discovered that Hard X-ray inversion under-estimates the counter-current drive of the new PAM LH antenna [9], thus suggesting a more reversed q-profile. Both options have therefore been considered.

Linear regime The normalized linear growth rate $\lambda \equiv \gamma\tau_A$ of the $n = 3$ mode is determined from the linear phase of the numerical simulations, as a function of diamagnetic rotation, measured by the parameter $\alpha \equiv 1/(\tau_A \omega_{ci})$ (τ_A is the Alfvén time and ω_{ci} the ion cyclotron pulsation). Only $n = 0$ and $n = 3$ mode numbers are retained here. For the original equilibrium, the $n = 3$ mode is found to be linearly stable above $S = 5 \times 10^7$ in the absence of diamagnetic rotation, but becomes unstable for finite α with a maximum growth rate in the regime of interest for the experiment (figure 4). As the Lundquist number S_0 is increased toward the experimental value ($S_0^{exp} \sim 6 \times 10^8$), the diamagnetic destabilization gets more pronounced by scaling with S at a smaller power than the resistive tearing mode ($\lambda \propto S^{-3/5}$). For the modified equilibria, the growth rate of the $n = 3$ mode increases with the q-profile reversal. The destabilization mechanism has not been precisely identified, but it is related to a toroidal curvature effect in the electron diamagnetic rotation. It is compensated by a stabilizing effect at higher α, that be-

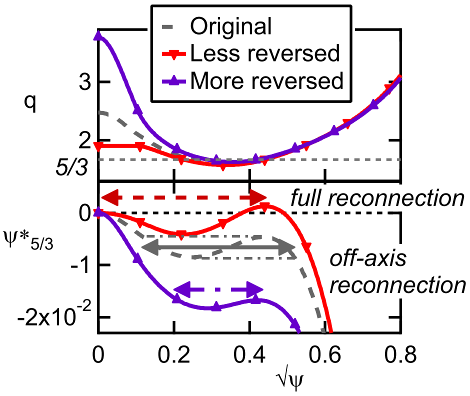

Figure 3: *q-profiles (top) and associated ψ^* (bottom).*

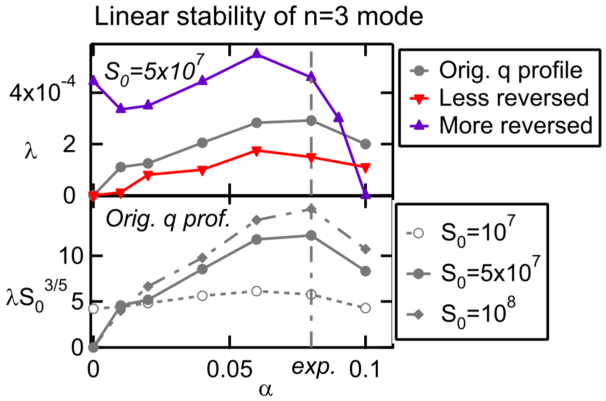

Figure 4: *Growth rate of $n = 3$ mode as a function of α.*

comes dominant at higher S [2], so that the more reversed q-profile may be linearly stable at $\alpha = 0.08$ and $S_0 = S_0^{exp}$. The competition between $n = 1$ and $n = 3$ modes depends therefore on the detailed core q-profile shape (from the point of view of equilibrium reconstruction), and on the Lundquist number that is used (from the point of view of simulation). Note that the $n = 1$ mode stability is weakly affected by α, and that neoclassical friction has a weak effect on linear stability in this case.

Mode structure and confinement degradation Non linear simulations have been performed where the evolution of toroidal mode numbers from $n = 0$ to $n = 4$ is computed. Synthetic temperature signals have been produced from the numerical simulations and they have been analyzed using the same analysis tool as experimental ECE data. Without two fluid effects ($\alpha = \mu_i = 0$), only the more reversed q-profile leads to a crash induced by the DTM on $q = 5/3$. But when $\alpha = 0.08$, the saturation level of the $n = 3$ mode is small for all q-profiles (fig. 5), $\delta T_e/T_e \sim 5\%$ only (fig. 6), and it is finally the $n = 1$ mode that is producing the crash. In particular, there is no full reconnection of the $n = 3$ DTM for the flatter q-profile, in contrast with $\omega^* = 0$ expectations [7]. It is only when $\mu_i \neq 0$ that $\delta T_e/T_e$ can compare in shape and amplitude with the observations ($\delta T_e/T_e \sim 20\%$ for original q-profile, $\delta T_e/T_e \sim 10\%$ for the less reversed one) (fig. 6). For the confinement degradation to be driven by the $n = 3$ DTM as experimentally observed, it is moreover necessary that the q-profile is more reversed than the original one (fig. 5), although the crash is not as complete as observed. Additional physics like electron inertia is possibly leading the $n = 3$ dynamics above $\delta T_e/T_e \sim 15\%$, where the crash becomes extremely fast.

Conclusion Close comparison between experimental measurements and non linear MHD simulations allows evidencing the manifestation of bi-fluid effects on the Double Tearing Mode.

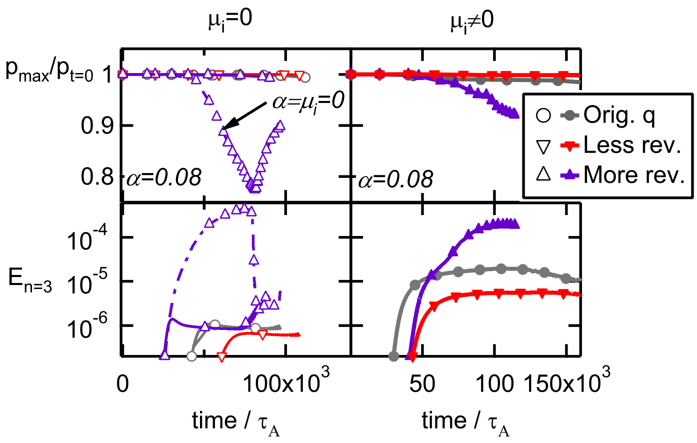

Figure 5: *Pressure degradation (top) and magnetic energy of $n = 3$ mode (bottom), for $\mu_i = 0$ (left) and $\mu_i \neq 0$ (right).*

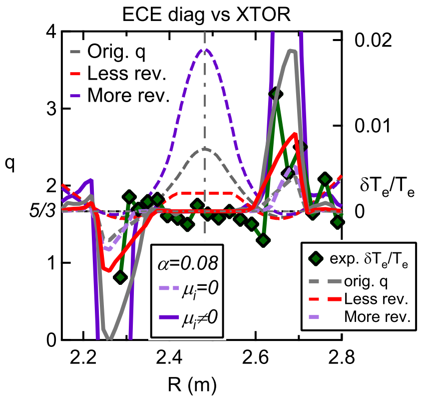

Figure 6: *MHD perturbation from experiment and from simulations.*

If the q-profile is not more reversed that found from Hard-X-ray reconstruction of LH current drive, electron diamagnetic destabilization is mandatory for explaining the growth of the DTM on $q = 5/3$. But even if this reversal is under-estimated, the DTM saturates at low amplitude and ω^* effect prevents a full reconnection. Another bi-fluid effect, the ion neoclassical viscous force, is therefore required in any case for explaining the observed level of $\delta T_e/T_e$ around $q = 5/3$. The rapidity of the last part of the crash ($\delta T_e/T_e > 15\%$) may involve other physics not covered by the code (e.g. electron inertia).

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