MHD modes associated to hollow current density profile configuration: Experiment and Modelling

P. Maget 1), G.T.A Huysmans 1), H. Lütjens 2), Ph. Moreau 1), N. Schaeffer 1), J.-L. Ségui 1)

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

2) *Centre de Physique Théorique, Ecole Polytechnique, 91128 PALAISEAU Cedex, France.*

e-mail contact of main author: patrick.maget@cea.fr

Abstract Hollow current density profiles often exist in Tokamak discharges, either transiently in the current ramp up, or in stationary phases where their main interest is to be generally associated with improved core confinement. Such a configuration is particularly relevant for Steady-State non-inductive scenarios where the self-driven bootstrap current dominates, as envisaged for ITER, or where external current drive peaks off-axis, as in Tore Supra. The reversed safety factor profile then obtained is moreover generally considered to reduce turbulent transport and form Internal Transport Barrier. However, MHD limits associated to such plasmas can be detrimental for the energy confinement, or even for the plasma control, due to dual-resonant surfaces. Experimental analysis of MHD activity from Tore Supra experiments, as well as non-linear numerical simulations with the XTOR code [1] probe our understanding of the underlying processes, and show that standard MHD model misses part of the acceptable operational domain. At higher pressure, the Infernal Mode dynamics in hollow current profile configuration is studied, and found to trigger secondary kink instability.

1 Introduction

Plasma discharges with hollow current density profiles exhibit a rich variety of non-linear MHD dynamics, and their MHD-free operational window is often difficult to determine in a reliable way. Fully non-inductive experiments performed in Tore Supra are used for evaluating the capability of non-linear MHD codes to reproduce experimental observations. This exercise shows that the standard one fluid MHD model is generally adequate for understanding the impact of Tearing modes. Full reconnection of the n=1 Double-Tearing Mode is predicted by simulations with XTOR [1], in agreement with experimental observations of global or off-axis crashes. Appropriate rescaling of dimensionless coefficients allows recovering in the simulations the $q = 2$ sawtooth regime first reported in [2], as well as the evolution to a saturated state with large confinement degradation when the $q = 2$ surface is moved outwards, as seen in Tore Supra experiments. However, experimental realization of steady-state non-inductive discharges with $q_{min} \sim 3/2$ are predicted to be strongly perturbed by the growth of the (2,1) mode, which is not systematically the case. The reason why the MHD model fails to reproduce the favourable cases is shown to originate from finite heat transport, which removes the curvature stabilization at low resistivity. Additional physics is required for providing a stabilizing mechanism acting on the n=1 mode, and recovering the operational domain where reliable discharges can be obtained.

Electron diamagnetic rotation is a natural candidate [3, 4], and we find with a reduced MHD, cylindrical model that a low amplitude saturation state exists for the (2,1) mode, although in conditions with lower transport and higher ω_e^* compared to experiment.

At higher beta, modes due to proximity to ideal limits (Infernal Mode) or to unfavourable interchange configuration (Resistive Interchange) enter into play. The Infernal Mode has generally severe consequences on the plasma discharge [5, 15, 6, 7], as inferred from numerical studies [8, 14]. But secondary instabilities can also be triggered, with higher growth rates. We show an example where in a hollow current profile equilibrium the Infernal Mode can destabilize a kink mode if heat transport is not strong enough to smooth the pressure gradient [9].

2 Non-linear MHD regimes of Tore Supra non-inductive discharges

Steady-state non-inductive discharges of Tore Supra are limited by the growth of MHD instabilities at $q = 2$, generally Double-Tearing Modes. These modes are identified as precursors to minor off-axis crashes, as well as to global core temperature crashes. Moreover, the plasma confinement regime resulting from this MHD activity at $q = 2$ varies from periodic relaxations with intermittent MHD mode to steady degraded energy confinement with stationary, large MHD modes. Finally, it appears that similar experimental discharges can either enter in a degraded confinement regime due to n=1 mode, or stay with a small n=2 MHD activity. Non-linear MHD simulations have been used for understanding this variety of behaviour. The XTOR code solves standard one-fluid full MHD equations including finite heat transport, in toroidal geometry:

$$
\begin{aligned}
\rho\partial_t \mathbf{v} &= -\rho\mathbf{v}\cdot\nabla\mathbf{v} + \mathbf{J}\times\mathbf{B} - \nabla p + \nu\nabla^2\mathbf{v} \\
\partial_t \mathbf{B} &= \nabla\times(\mathbf{v}\times\mathbf{B}) - \nabla\times\eta\,(\mathbf{J} - \mathbf{J_{bs}} - \mathbf{J_{cd}}) \\
\partial_t p &= -\Gamma p\nabla\cdot\mathbf{v} - \mathbf{v}\cdot\nabla p + \nabla\cdot\chi_\perp\nabla p + ... \\
& \quad ... + \mathbf{B}\cdot\nabla[\chi_\parallel(\mathbf{B}\cdot\nabla p)/B^2] + H
\end{aligned}
$$

where $\mathbf{J_{bs}}$ is the bootstrap current, $\mathbf{J_{cd}}$ is the imposed current source, $H = -\nabla\chi_\perp\nabla p(t = 0)$ is the heat source term, ν is the viscosity, ρ the density, and $\chi_\parallel$ and $\chi_\perp$ the parallel and perpendicular transport coefficients. The plasma resistivity evolves with pressure ($\eta(t) \propto p(t)^{-3/2}$). Transport coefficients are chosen in order to keep the correct response of pressure during either the mode growth (for linear studies) or the equilibrium evolution (for fully developed non-linear regime studies), while taking an artificially large resistivity. The code is run on the basis of experimental magnetic equilibrium, determined after current diffusion simulations with the CRONOS code [10], cross-checked with MHD mode structures.

The issue of non-linear impact of the Double-Tearing Mode on confinement has been addressed by varying the total current in the equilibrium. A small change allows to vary the expected region of full reconnection of the helical magnetic flux ($\psi^* = \int d\psi(1 - q/q_{res})$ with $q_{res} = 2$ here). As the reconnection region passes from off-axis to global, the impact

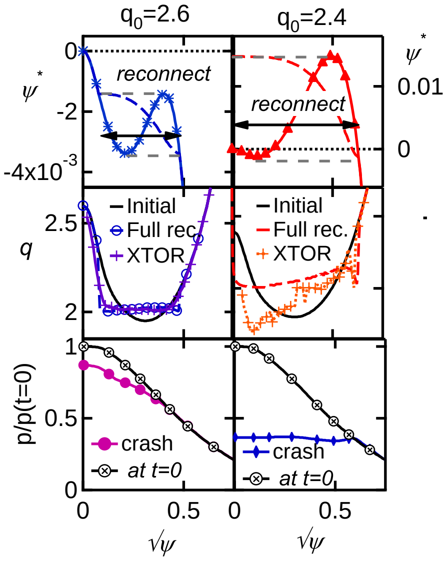

Figure 1: *Full Reconnection of the DTM from heuristic model (top and middle) and from XTOR (middle and bottom), with different impact on confinement (bottom).*

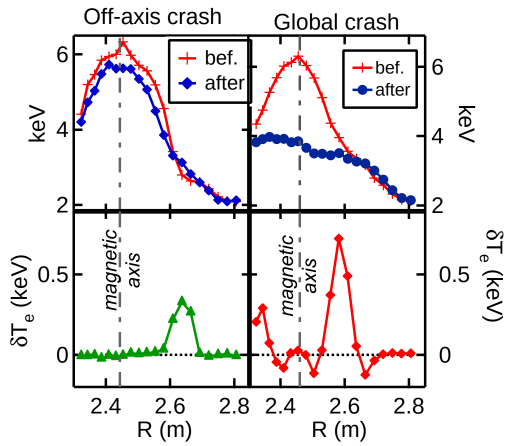

Figure 2: *Off-axis and global T_e-crashes (top); radial structure of the MHD precursor (bottom).*

of the Double-Tearing Mode goes from a modest reduction of the pressure gradient to a global pressure crash in the plasma core (figure 1). The results of the non-linear simulations are therefore in line with the experimental observations shown in figure 2, where in the same non-inductive pulse with slightly different localisation of the double-resonant $q = 2$ surfaces (as evidenced by the radial structure of δT_e), the impact of the mode varies significantly.

The fully developed non-linear regime of hollow current density profile configurations is also an important point. Indeed, two different regimes can be envisaged, and are indeed observed. The first one consists of periodic relaxations, and is nicely illustrated by the so-called $q = 2$ sawtooth regime [2]. In the other regime, the mode grows to saturation, and results in a situation with degraded confinement and large MHD activity, as in the so-called MHD regime of Tore Supra [11]. We find that in Tore Supra the two regimes can be discriminated by considering the inversion radius of the MHD crash. When the inversion radius is inside $\sqrt{\Phi} \approx 0.3$ (with Φ the normalized toroidal magnetic flux), the fully developed non-linear regime consists of periodic relaxations, while the mode saturates at large amplitude when $\sqrt{\Phi} > 0.3$ (figure 3). Using the same rescaling of the total plasma current as before, we have increased the radial position of the $q = 2$ surface in order to compare the non-linear evolution of the plasma after the MHD crash. When $q = 2$ is at $\sqrt{\Phi} = 0.36$, the MHD mode is a Double-Tearing and the full reconnection of the mode removes the $q = 2$ surface after the crash, allowing the pressure to recover before the Double-Tearing becomes

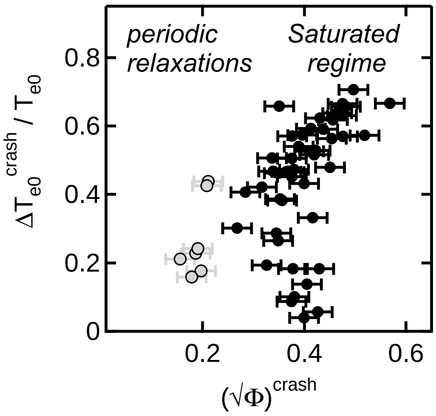

Figure 3: *Position of the inversion radius of T_e crash for periodic and saturated regimes in Tore Supra.*

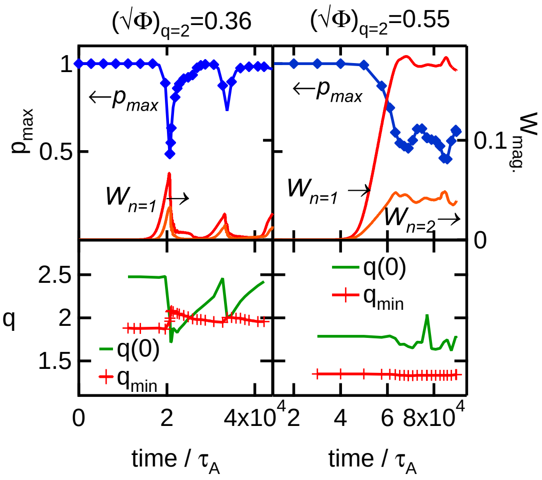

Figure 4: *Non-linear XTOR simulations where the $q = 2$ surface position is varied by rescaling the total current.*

unstable again. We then recover the $q = 2$ sawtooth regime. For $q = 2$ at $\sqrt{\Phi} = 0.55$, the MHD mode is a single tearing that saturates at large amplitude, and the plasma evolves to a new state with large confinement degradation and MHD activity, as seen experimentally (figure 4).

However, we have experimental evidence that non-inductive experiments with $q_{min} < 3/2$ and $q = 2$ at about $\sqrt{\Phi} \approx 0.5$ can be free of large $n = 1$ MHD activity, although this is not always the case. The longest Tore Supra experiments, for example, often have low amplitude saturated $n = 2$ MHD activity that produces minor confinement loses. The stability of the $n = 1$ mode is such cases shows that physics effects not covered in the standard MHD model can extend the acceptable operational domain.

3 Investigations on $n = 1$ mode stability

On the basis of a magnetic equilibrium from a discharge without detectable $n = 1$ MHD activity, we have investigated the linear stability of the $n = 1$ mode. We find that the standard MHD model without transport predicts a stable $n = 1$ mode at the experimental resistivity (figure 5). This is in agreement with the theory, where toroidal curvature adds a stabilising contribution that increases at low resistivity until full linear stability [12]. For tearing modes however, which has very small growth rate in experimental conditions due to low resistivity, neglecting transport is not justified. And full stabilisation is no longer expected [17], as verified with XTOR.

We therefore investigate if additional physics, beyond the standard MHD model, could

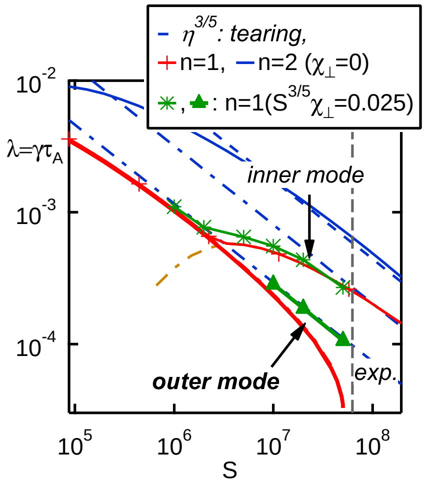

Figure 5: *Linear growth rate of $n = 1$ mode without and with transport.*

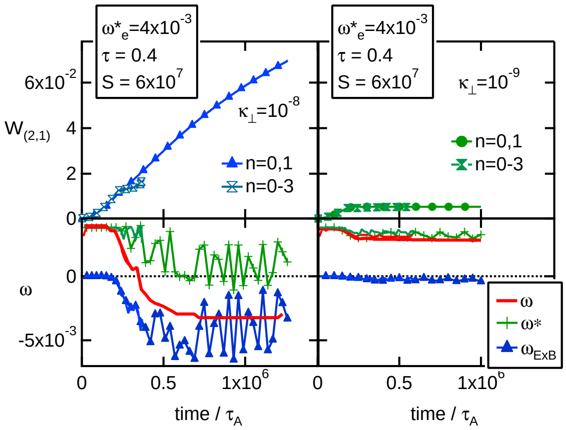

Figure 6: *Outer (2,1) island width (top) and mode pulsation (bottom) from non-linear reduced MHD simulations with different perpendicular diffusivities.*

explain the absence of detectable island on $q = 2$. Electron diamagnetic rotation could be the actual mechanism. It is known indeed to open the way to an additional, non-linearly driven, saturated island regime at small width [3, 4]. This is confirmed by non-linear MHD simulations in cylindrical geometry with a 4-field isothermal MHD model evolving the poloidal magnetic flux, electrostatic potential, electron pressure and parallel ion velocity [13]:

$$\begin{aligned}
\partial_t\psi &= \eta\nabla_\perp^2\psi - \nabla_\parallel(\phi - \delta p) + e && (1)\\
\partial_t W &= \nu\nabla_\perp^2 W + [W, \phi + \delta\tau p] - \nabla_\parallel J + \delta\tau\,[\nabla_\perp p; \nabla_\perp\phi] && (2)\\
\partial_t p &= \kappa_\perp\nabla_\perp^2 p + [p, \phi] - \beta\nabla_\parallel(v - 2\delta J) + S_p && (3)\\
\partial_t v &= \nu_\parallel\nabla_\perp^2 v + [v, \phi] - \frac{1+\tau}{2}\nabla_\parallel p + \delta\tau\beta\frac{1+\tau}{2}[p, v] && (4)
\end{aligned}$$

with e and S_p the source terms, $W = -\nabla_\perp^2\phi$ and $J = -\nabla_\perp^2\psi$, $[f, g] \equiv x^{-1}\{\partial_x f\partial_\theta g - \partial_x g\partial_\theta f\}$, $\nabla_\parallel \equiv \epsilon\partial_\varphi - [\psi, .]$ and $[\nabla_\perp p; \nabla_\perp\phi] = [\partial_x p, \partial_x\phi] + [x^{-1}\partial_\theta p, x^{-1}\partial_\theta\phi]$. The electron diamagnetic pulsation is then $\omega_e^* = -(m/x)\delta(dp/dx)$ with $x = r/a$.

The current density profile is fitted from the original toroidal equilibrium, the pressure profile is analytic ($p(x) = p_0\,(1 - x^2)^3$ with $x = r/a$), and we take the experimental resistivity ($S = 6 \times 10^7$), a ratio $\tau = T_i/T_e = 0.4$ and $\beta = 3 \times 10^{-3}$ as in the experiment. Two different saturated regimes are found, one with a large saturated island ($w/a \geq 0.07$) as found with the standard MHD model, and another one with a small saturated island ($w/a \approx 0.006$) (figure 6). In the small island regime, the mode frequency follows closely the local electron diamagnetic frequency, while in the large island regime, the mode is slowed and is nearly steady in the local plasma frame (which rotates at ω_{ExB}). However, the small island regime is only accessible when the diffusion coefficient is at the collisional level ($\kappa_\perp^{coll.} = \eta(1+\tau)/2 \approx 3.5 \times 10^{-9}$), while the stabilizing contribution from ω_e^* is lost as the pressure is smoothed by more realistic values of $\kappa_\perp$ (i.e. $\kappa_\perp \sim 10^{-7}$). Investigations using the XTOR code with a simple modified Ohm's law ($\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta\,(\mathbf{J} - \mathbf{J_{NI}}) - \frac{1}{1+\tau}\frac{\nabla_\parallel p}{en}$) indicate that toroidal geometry does not provide a sufficient stabilizing effect to compensate for the reduction of diamagnetic contribution due to transport in the non-linear regime.

In summary, the absence of $n = 1$ mode in successful non-inductive discharges is still not clearly understood. Electron diamagnetic rotation could potentially provide the possibility of a small saturated island regime that would be consistent with the fact that the island is not detected, but the two-fluid models that have been used limit the access to this regime to diffusion coefficient. A more comprehensive two-fluid MHD model may correct this discrepancy. It remains that the actual reliable operational domain is larger than predicted by the standard MHD model.

4 Non-linear Infernal mode in hollow current profile plasma

The extrapolation of present Tore Supra non-inductive experiment to higher performance conditions (as predicted by standard MHD model implemented in the CASTOR code [16]) shows first a stabilization of the Tearing Mode when increasing β_N, and then a destabilization of the Infernal Mode (figure 7). This finite-n pressure driven mode develops in low magnetic shear region, below the $n = \infty$ ballooning limit [5].

Its non-linear growth was studied without transport in cylindrical geometry [8], and in toroidal geometry [14], showing potentially strong impact of the mode on energy confinement, as seen in various experiments [15, 7, 6]. Toroidal geometry and finite transport effects have been studied with the XTOR code on the basis of a JET-like Advanced Tokamak discharge, with $q_{min} = 1.32$ and artificially increased pressure ($\beta_N \sim 3.6$) so that the $m = 4, n = 3$ Infernal Mode is ideally unstable. The safety factor profile is strongly reversed in the plasma core, and has a large off-axis region with vanishing magnetic shear. Non-linear simulations are performed at a Lundquist number $S = 5 \times 10^6$, in two different transport regimes. In the first one, $\tau_R/\tau_E \equiv S\chi_\perp = 10$, while in the second case, $\tau_R/\tau_E = 1$ which means that heat transport is then one order of magnitude higher. In both cases, anisotropic diffusivity is assumed, with

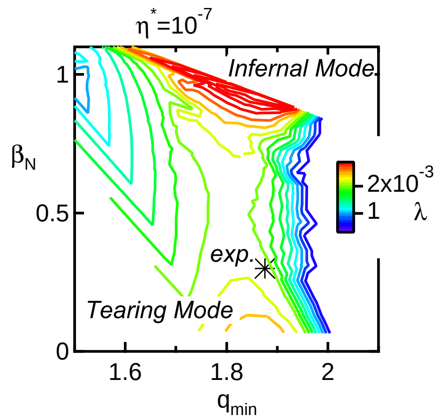

Figure 7: *Extrapolation of linear resistive modes from Tore Supra experiment (*) to higher* β_N *as a function of* q_{min}.

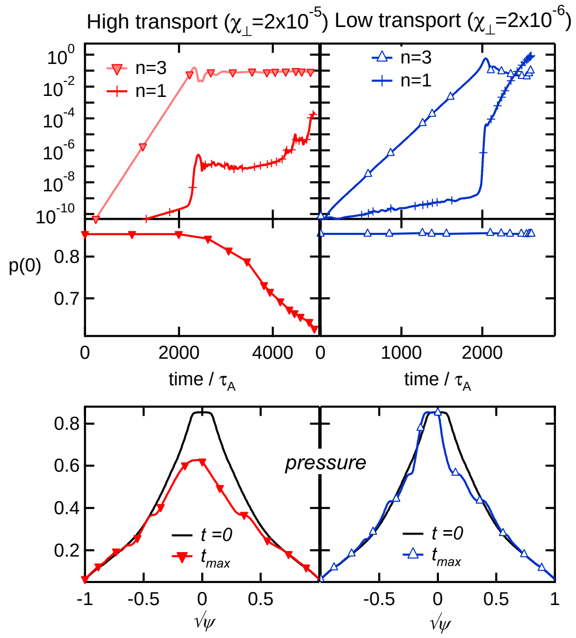

Figure 8: *Non-linear XTOR simulations of the Infernal Mode with different diffusivities.*

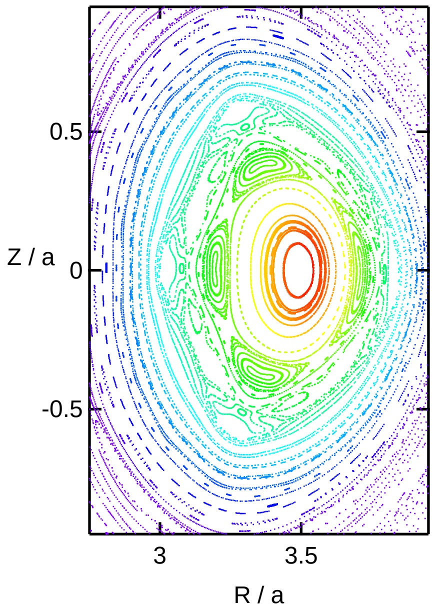

Figure 9: *Poincaré plot of the (4,3) Infernal mode.*

$\chi_\parallel/\chi_\perp = 10^8$. The two cases are shown in figure 8.
Due to the hollow current profile, the region where the Infernal Mode directly affects the pressure is located off-axis, as evidenced by a Poincaré plot in the non-linear regime (figure 9). When the heat transport coefficient is large enough to smooth the large pressure gradient that develops inside the Infernal Mode region, the core confinement is rapidly degraded (figure 8, left). However, when heat transport is lower, the pressure gradient at the edge of the core confined region exceeds the threshold for a faster growing $m = 1, n = 1$ instability (figure 8, right). These simulations suggest that finite-n ballooning instabilities such as the Infernal Mode could not be afforded in experiments with hollow current profiles, with either strong confinement losses or a disruption.

5 Conclusion

MHD limits associated to hollow current density profile discharges are studied and compared to non-linear MHD predictions for Tore Supra experiments. Regimes of off-axis and global crashes, as well as sawtooth regime associated to the (2,1) Double-Tearing Mode are correctly reproduced. As q_{min} is decreased, the (2,1) mode becomes a single tearing and periodic relaxations are replaced by saturation, in agreement with the observed soft MHD limit in Tore Supra non-inductive discharges. The confrontation of experimental observations to non-linear code simulations evidences however the existence of a larger acceptable operating domain in Tore Supra compared to code prediction, suggesting a favourable role of missing physics in the standard MHD model. Diamagnetic rotation is a possible candidate, but there remain an issue concerning transport coefficient, because they should in principle be too large to allow the existence of a small island regime as foreseen. This study on Tore Supra shows that anticipating the impact of MHD modes on future devices is a key issue that requires careful validation of numerical codes on present experiments. Investigations of high-β hollow current equilibria have first focussed on the Infernal Mode, and we shown that in the non-linear regime, steep pressure gradients can be produced that destabilizes faster secondary mode.

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