Non-linear simulation of double-tearing modes in fully non-inductive discharges

P. Maget, H. Lütjens[1], G. T. A. Huysmans, X. Garbet, J.-F. Luciani[1], M. Ottaviani

Association Euratom-CEA, CEA/DSM/DRFC, Cadarache, 13108 St Paul lez Durance, France

[1] *Centre de Physique Théorique (Ecole Polytechnique), Palaiseau, France*

Introduction

In fully non-inductive tokamak discharges, hollow current density profiles can result from a dominant contribution of the bootstrap current, or from the off-axis deposition of an external current source. Such discharges are potentially unlimited in time, but are prone to the triggering of double-tearing modes, which in their non-linear evolution may cause a rapid confinement degradation over a large region of the plasma. Moreover, such degration has a direct impact on the current sources themselves: the bootstrap current is weakened in the region where the mode develops, and the radial profile of the external source can also be modified. In Tore Supra, where the use of Lower Hybrid waves allows to operate fully non-inductive discharges, the full reconnection of the double-tearing mode has dramatic impact on the discharge. It leads to a regime where permanent MHD activity sets in, the LH power deposition profile is modified and the current drive efficiency is lower. As a consequence, the confinement in the plasma core is degraded and the loss of fast electrons causes damages to the machine [1].

The non-linear evolution of the double-tearing mode is studied with the XTOR code [2], on the basis of an experimental Tore Supra magnetic equilibrium. The plasma current density is assumed to be driven non-inductively, i.e. we assume a constant driven current $\mathbf{J_{cd}} = (\mathbf{J} - \mathbf{J_{boot}})|_{(t=0)}$, and the toroidal rotation is assumed to be zero.

Figure 1: Safety factor profile #33986 at $t = 26\ s$.

Linear stability

The magnetic equilibrium (figure 1, case $q(0) = 2.495$) corresponds to a Tore Supra pulse (#33986), in a fully non-inductive scheme ($I_p = 0.5MA$, $B = 3.8T$, $P_{LH} = 3MW$). It comes from a current diffusion simulation done with the CRONOS code [3], where the LHCD current is deduced from the Abel inverted bremsstrahlung emission tomogra-
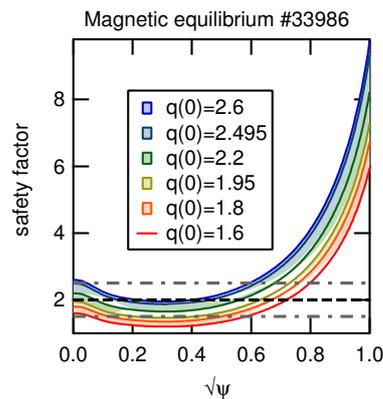
phy (Hard X-ray) in the range 60-80 keV.

A scan in the edge safety factor (renormalization of the total current) is first performed in order to study more generally the MHD stability of such a magnetic config-uration. Transport coefficients normalized to τ_A/a^2 are taken as $\chi_\perp = 5.10^{-7}$ and $\chi_\parallel = 50$, those values being consistent with the experiment when taking into account the heat flux limit in the parallel direction. The charac-teristic radial scale introduced by finite transport is larger than the resistive layer width, and weakens the stabilizing field line curvature effect [4]. This configuration is found to be linearly unstable to the $n = 1$ mode for $q_{min} < 2$ while a stable window is found in the range $q_{min} \in [2, 2.4]$ (figure 2).
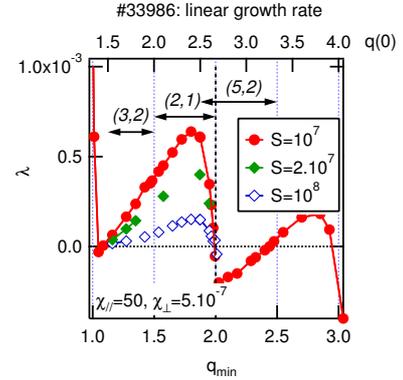

Figure 2: Linear stability ($\lambda = \gamma\tau_A$)

The linear stability of the magnetic configuration of Tore Supra non-inductive discharges is therefore prone to the triggering of double-tearing modes as soon as q_{min} is below 2. However we know from the experiment that the growth of a double-tearing mode is a problem for the operation only in a restricted range of q_{min} [1]. Indeed, the region of the plasma affected by the mode changes with q_{min}, and the non-linear evolution of the mode can be quite different.

Non-linear simulations

We first consider the non-linear evolution without treating the bootstrap current effect, and with $S = 5.10^6$ (it is around 10^8 in the experiment). In figure 3, we show the pressure profile at the time when the core pressure is minimum. When $q(0)$ is sufficiently below 2, the single tearing mode on $q = 2$ grows and saturates without affecting the pressure profile in the plasma core. As $q(0)$ is approaching 2, the single tearing mode perturbation affects the entire plasma core region, producing a large crash of the pressure. For $q(0)$ above 2 (double-tearing mode on $q = 2$), a crash corresponding to a full reconnection of the mode is obtained. As the region with $q < 2$ becomes narrower, the crash has less effect on the core pressure profile.

These results compare well with experimental observations in pulse #33986. Off-axis crashes of the electron temperature are sometimes observed, with a MHD precursor that has the typical door-like shape of a double-tearing mode (figure 4, left). This is consistent with the simulation with $q(0) = 2.6$. Other observations show clearly that the full reconnection of the double-tearing mode flattens the temperature profile on a large core region up to the outer boundary of the double-tearing mode precursor (figure 4, right), as in the simulation with $q(0) = 2.2$.

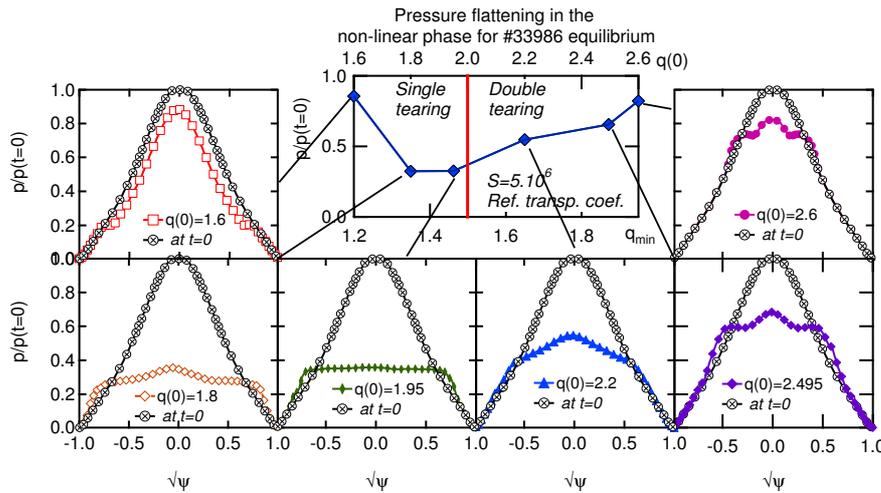The non-linear dynamics of the mode differs from one case to the other. In the two extreme

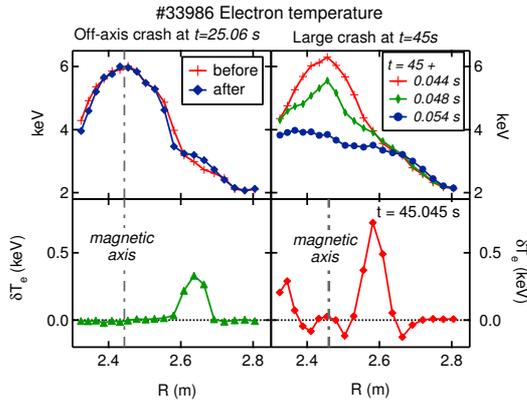Figure 3: Max. amplitude of pressure profile flattening for different values of $q(0)$.
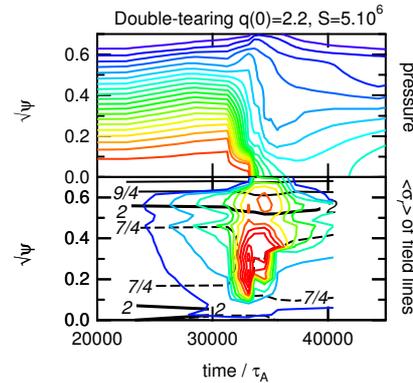

Figure 4: Off-axis and global T_e-crashes.

Figure 5: Propagation of magn. pert.

cases ($q(0) = 1.6$ and $q(0) = 2.6$), the mode reaches a saturated state with one or two islands. In the intermediate cases, the double-tearing mode reconnection produces a large ergodic region and a pressure crash. Afterwards, the magnetic energy decays and the pressure increases again, giving rise to a sawtooth-like behaviour. The dynamics of the crash is illustrated for the case $q(0) = 2.2$ in figure 5. The bottom plot shows the standard deviation of magnetic field lines over 500 toroidal turns, obtained from a Poincaré map. The magnetic perturbation on $q = 2$ propagates at the closest resonant surface ($q = 7/4$ since $n_{max} = 4$ in this run) and then goes to the inner $q = 7/4$ surface before full ergodisation of the plasma core up to $q = 2.5$ at the crash. Finally, note that the magnetic configuration never saturates with two well separated islands. Instead, the separatrix of the inner and outer islands merge (fig. 6, left).
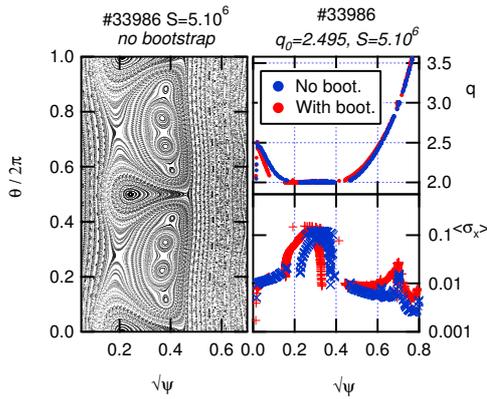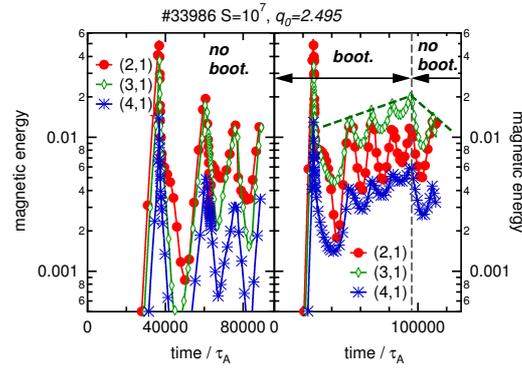
Figure 6: Poincaré plot ($q_0 = 2.495$)

Figure 7: Bootstrap effect.

Bootstrap current effect

We have compared simulations with and without the bootstrap current ($\approx 17\%$ of total current) for the case $q(0) = 2.495$ at $S = 10^7$ (figure 7). When bootstrap is considered, the tearing mode on $q = 3$ emerges after the DTM crash. When cancelling the bootstrap current, the $(3, 1)$ mode decreases, showing that the main effect is the helicoidal bootstrap current perturbation and not a profile effect, although the pressure crash has slightly changed the q-profile (see fig. 6, right).

Conclusions and perspectives

A typical hollow current density discharge from Tore Supra non-inductive experiments is found linearly unstable to $n = 1$ mode as soon as $q_{min} < 2$, producing a large pressure crash when $q(0)$ is close to 2. This is due to the propagation of the magnetic perturbation to inner resonant surfaces. A limited impact on the pressure is only obtained for $q(0) \leq 1.6$ or $q(0) \geq 2.6$, and we never obtain separate saturated islands. This contrasts with simulations in cylindrical geometry [5, 6]. In the saturated non-linear regime, the DTM is characterized by the merging of inner and outer island separatrix. Taking into account the bootstrap current modifies the dynamics of the equilibrium (loss of bootstrap current) and adds a destabilizing term due to the bootstrap current perturbation. This latter effect is found to be responsible for the growth of a tearing mode on $q = 3$, which is therefore a Neoclassical Tearing Mode (NTM) destabilized by the DTM.

References
[1] P. Maget et al, *Nuclear Fusion* **45**, 69 (2005)
[2] K. Lerbinger and J.-F. Luciani *J. Comp. Phys.* **97**, 444 (1991)
[3] Basiuk V et al 2003 *Nuclear Fus.* **43** 822
[4] Lütjens H Luciani J F and Garbet X 2001 *Phys. of Plasmas* **8** 4267
[5] Carreras B., Hicks H.R., and Waddell B.V. 1979 *Nuclear Fusion* **19** 5863
[6] Yu Q. and Guenter S. 1999 *Nuclear Fusion* **39** 487