

## MHD issues in Tore Supra plasmas with non-inductive current drive

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### Introduction

Non-inductive tokamak plasmas open the way to steady-state operation, with the use of external current sources to complement the intrinsic bootstrap current. Such operation is generally characterized by (i) a flat or hollow current profile density, and (ii) the presence of a fast particle population driven by the external current source. In Tore Supra, external current drive is provided by Lower Hybrid waves, allowing for the study of MHD issues in moderate- $\beta$  steady-state plasmas. In fully non-inductive discharges, LH waves provide  $\sim 85\%$  of the total current and drive a hollow current density profile inside typically  $r/a \sim 0.2$ . The minimum of the safety factor is ranging between 1.5 and 2, and  $\beta_p \sim 0.5$ . In such condition, the plasma is subject to tearing instabilities, in particular Double-Tearing Modes (DTM) at  $q_{min} < 3/2$  or  $q_{min} < 2$  [1, 2], and fast electron driven modes for  $q_{min} \sim 3/2$  and  $q_{min} \sim 2$ . In the present work, we present results on the MHD activity and associated confinement regimes in this type of plasma discharges. Experimental observations are compared to non-linear simulations with the full MHD code XTOR [3], which solves the evolution of magnetic field, velocity and pressure including transport, with a modelled bootstrap current and momentum input.

### Fast electron driven mode: characterization

A coherent mode is sometimes observed at a frequency above the diamagnetic frequency of tearing modes (7-15 kHz instead of 1-4 kHz), suggesting that fast electrons are driving the mode. This fast electron driven mode (FEDM) is closely related to the double-tearing mode configuration, and can be observed simultaneously at the same localization (figure 1). This mode could be an electron fishbone mode, associated to a double-kink configuration instead of the already observed internal kink [4]. The energy of resonant electrons deduced from the mode frequency would be in the range 30-80 keV, which would be consistent with the energy of the electron tail driven by LH waves ( $> 20$  keV). This fast electron driven mode is also attached to the Oscillating Temperature Regime (O-regime [5]), where it accompanies the temperature oscillation with large frequency excursion (figure 2). The presence of this mode during the O-regime shows that this incomplete transition to improved confinement occurs for  $q_{min}$  at a low

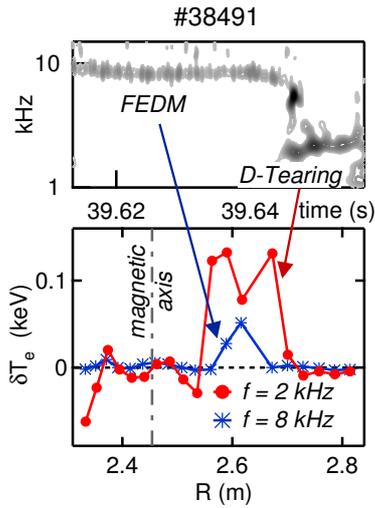


Figure 1: FEDM and DTM radial structures (top); spectrogram (bottom).

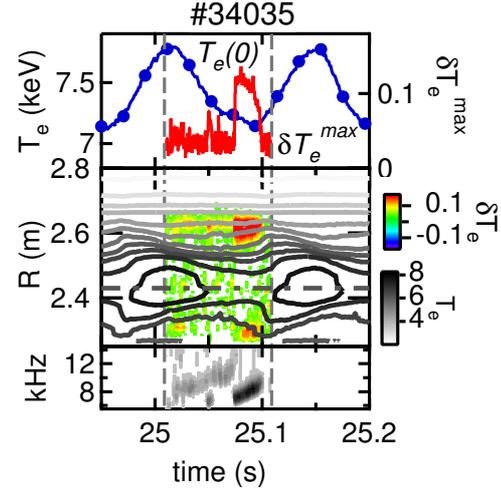


Figure 2: Intermittent FEDM during O-regime: time trace, contour of  $T_e$  and  $\delta T_e$ , spectrogram.

order rational value [6], thus re-enforcing other observations of Internal Barrier formation at rational  $q_{min}$  values using another MHD mode (Alfvén Cascades) as a diagnostic [7, 8].

### Impact of DTM on confinement: observations and simulations

The hollow current density profile of Tore Supra non-inductive discharges is MHD-unstable due to tearing or Double-Tearing Modes (DTM) when  $q_{min} < 2$ . For numerical simulation, transport coefficients are determined by the condition that the confinement energy time is in the same ratio with respect to the resistive time as in the experiment ( $S\chi_{\perp} = (S\chi_{\perp})_{exp}$  with  $S = \tau_R/\tau_A$  the Lundquist number), and we take  $\chi_{\parallel}/\chi_{\perp} = 10^8$ . In such configuration where the steady state equilibrium is MHD-unstable, MHD modes manifest themselves either as periodic bursts or as a continuous perturbation. These two non-linear regimes are observed with the so-called  $q = 2$  sawteeth [9] for the case of periodic relaxations, and two forms of continuous regimes: one corresponds to the saturation of a single mode and has benign effect on the global confinement, while the other corresponds to the non-linear interaction of several modes with severe confinement degradation, and is called the MHD regime [10, 11].

The  $q = 2$  sawtooth regime, associated to a DTM, is correctly described in non-linear simulations with XTOR, showing periodic burst of MHD modes that flattens both the pressure and the safety factor in the plasma core (figure 3). The radial extent of the crash is found to follow the full reconnection model [12] (figure 4), thus explaining the off-axis or global crash observed experimentally by the extent of the region where the helical magnetic flux  $\psi^* = \int d\psi(1 - q/q_{res})$  reconnects [13] (here  $q_{res} = 2$ ).

The continuous regime with one single mode is experimentally found to be reliable: 6 minutes

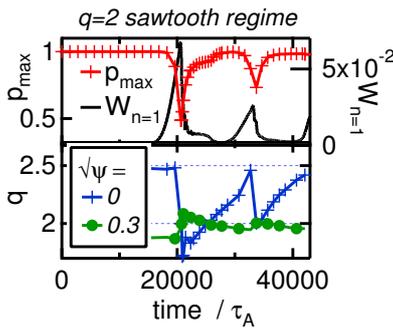


Figure 3:  $q = 2$  sawtooth regime (XTOR): core pressure and energy of  $n = 1$  mode (top), safety factor at centre and initial  $q_{min}$  position (bottom).

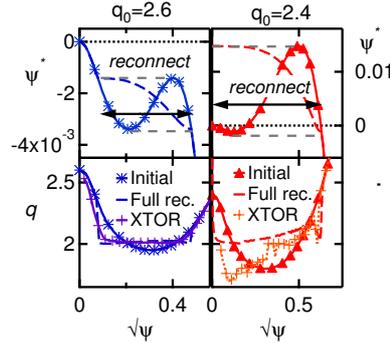


Figure 4: Full reconnection model (top) and XTOR results (bottom).

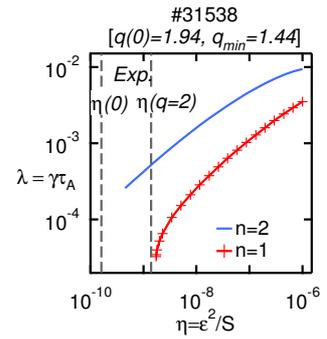


Figure 5: Linear stability of GigaJoule experiments down to exp. resistivity.

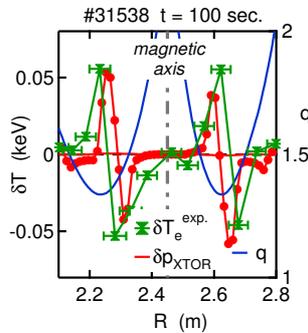


Figure 6: Experimental  $\delta T_e$  and simulated  $\delta p$  retaining only even  $n$ .

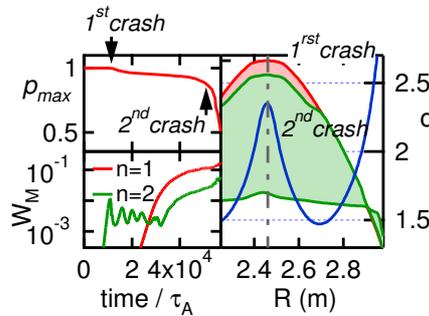


Figure 7: Double-crash similar to that observed in some experiments (cf. Ref. [10], fig. 9), retaining all  $n$ 's in XTOR.

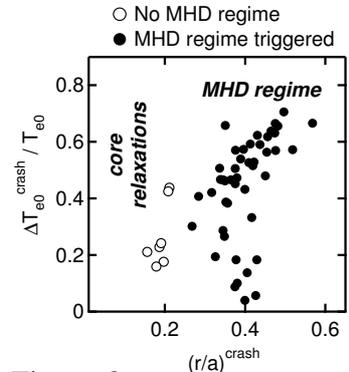


Figure 8: Relative temperature drop as a function of the inversion radius of the crash.

("GigaJoule") non-inductive discharges of Tore Supra [14] were actually performed in presence of a continuous tearing mode on  $q = 3/2$  [11]. However, the stability of the  $n = 1$  mode for this configuration is hardly reproduced in simulations. It can only be understood when using the experimental Lundquist number, and ignoring heat transport (linear stability analysis, CASTOR code [15], fig. 5). When keeping only even toroidal modes in XTOR, a saturated state with a pressure perturbation similar to that of the experiment is found (fig. 6). The situation with both  $n = 1$  and 2 unstable modes (fig. 7) is however also observed experimentally, giving rise to successive crashes on  $q = 3/2$  and  $q = 2$ .

The MHD regime is probably the result of several effects. It occurs when the pressure crash extends outside  $r/a \sim 0.3$  (fig. 8), and could be compared to simulations where the unstable  $q = 2$  surface is at a large radius, producing a saturated state with large MHD perturbations that prevent the pressure to recover its initial state. Also, the crash of electron temperature changes the deposition of LH waves thus favouring a bifurcation to a new equilibrium. The

effect of the perturbed bootstrap current has also been investigated numerically. It is found to broaden significantly ( $\sim 30\%$ ) the  $q = 3$  island [13], thus being a potential contributor to the sustainment of the MHD regime.

### Summary and perspectives

The MHD issues of steady-state non-inductive plasmas of moderate  $\beta_p$  is addressed in Tore Supra with  $q_{min} \in [3/2, 2]$ . A fast electron driven mode due to LH current drive is identified for  $q_{min}$  in the vicinity of 2 and  $3/2$ . It is identified as double-kink destabilized by the LH hot electron tail, and could be an electron fishbone mode. Its presence in the O-regime points towards a favourable effect of low order rational surfaces at  $q_{min}$  on anomalous transport, as suggested by other experiments diagnosed by Alfvén Cascades.

Tearing modes are unstable as  $q_{min}$  passes below 2. Their non-linear impact is generally well understood and reproduced by numerical simulations. In particular, the  $q = 2$  sawtooth regime is recovered using a transport coefficient that scales appropriately with the Lundquist number used in the simulation. For large pressure crash due to  $n = 1$  mode, the discharge bifurcates to the MHD regime, in a way comparable to simulations where MHD activity prevents the pressure to recover. Experiments with a stable  $n = 1$  mode are more challenging for numerical studies, as they could be explained by the high experimental Lundquist number. But linear stabilization at high  $S$  may be crucial for Advanced Tokamak experiments with  $q_{min} \leq 2$ : when extrapolating Tore Supra experiments to larger  $\beta$ , a stable window between the Double-Tearing and Infernal modes opens at high  $S$  [2]. The MHD study of Advanced Tokamak scenario, both in its transitory (present experiments) and steady-state (future tokamaks) phases should answer these issues [16].

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