*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.129 (2007)*

Non-linear MHD analysis of Advanced Tokamak Scenario

N. Schaeffer[1], P. Maget[1], H. Lütjens[2], G.T.A. Huysmans[1] and JET EFDA contributors[3]

[1] *Association Euratom-CEA, CEA/DSM/DRFC, Cadarache, St-Paul lez Durance, France*

[2] *Centre de Physique Théorique, CNRS UMR7644, Ecole Polytechnique, Palaiseau, France*

[3] *See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)*

Introduction

The advanced tokamak scenario [1, 2] is of primary interest when considering the development of a steady state operating fusion facility. It is characterized by an improved core confinement and a large fraction of non-inductive toroidal plasma current. This non-inductive current is provided by the bootstrap current complemented by external sources. The current density profile of such scenarii often have an off-axis maximum, associated with a negative central magnetic shear (NCS). The main operational limitations are due to MHD instabilities, leading to performance degradation or disruption [3].

In this study we will focus on the Magneto-Hydro-Dynamic (MHD) stability of the plasma core of pulses which contain a hollow current profile (a very low current density near the magnetic axis), and with a large region of almost zero magnetic shear.

A previous study [4] showed that the resistive interchange mode was responsible for the filling of the hollow current profile in DIII-D. Later, it has been shown that the resistive kink prevented the current density from becoming negative [5], thus limiting the depth of the hollow current profile.

Profiles and pulse details

In order to work on realistic profiles, we base our study on a JET shot (#66498, 1.9MA, 3T) which has a non-inductive current fraction of 55% according to CRONOS, and all the features described above [6]. First, the profiles from magnetic equilibrium reconstruction code EFIT constrained with Motional Stark Effect (MSE) data at $t = 3s$ [7] (before the full power operation) are used to start a CRONOS sim-

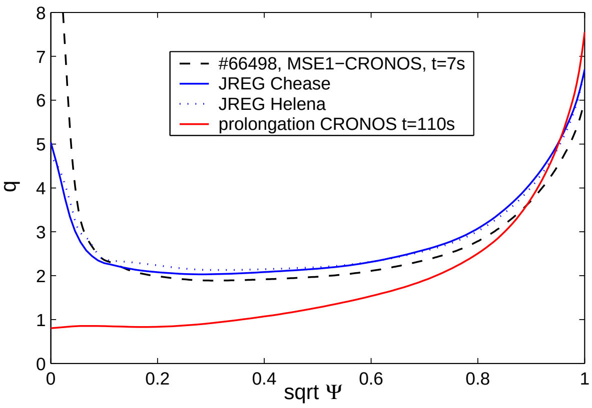

Figure 1: Safety factor profiles used in our study vs $\sqrt{\Psi}$ where Ψ is the poloidal flux.

ulation, letting the q-profile (q is the safety factor) evolve by resistive diffusion with the measured temperature profile. This gives the main q-profile for our study, at $t = 7s$ (fig. 1, black dashed trace). From this main q-profile, we also build two other profiles :

- regularized profiles (by rescaling the current profile in the NCS region) with a lower safety factor on the magnetic axis, based on the MSE measurements at $t = 7s$ (fig. 1, blue traces),
- and another with no NCS region at all (fig. 1, red trace).

The hollow current profile is not a steady-state feature, but according to CRONOS (current diffusion) it should persist during the pulse duration, but letting the equilibrium profile evolving for a long time (110s) with the sources maintained in their full power regime, the safety factor profile does not show a reversed shear region any more (fig. 1). However, the MSE measurements at $t = 7s$ indicates that the safety factor on the magnetic axis is much lower and experimental data shows the presence of MHD modes. It is thus reasonable to think that hollow current profile is partially filled by an MHD instability.

Stability

Firstly, we perform a stability analysis on the JREG profile (less hollow profile obtained with Helena, see fig. 1) using CASTOR[9], a code that computes linear MHD eigenmodes and eigenvalues, without taking transport into account. The Lundquist number for this study is $S = 10^6$.

The growth rate obtained are shown in figure 2 for different rescaled profiles (obtained using Grad-Shafranov equilibrium scaling laws), as a function of the minimum value q_{min} of the safety factor q.

In order to identify the modes, which all show similar amplitude profiles, we did a resistivity scan, that showed a growth rate which scales like $\eta^{1/3}$ suggesting resistive interchange, taking place at a resonant surface.

The analysis of the experimental data from the fast magnetic acquisition system (KC1M) between 6 and 8s shows:

- strong $n = 1$ bursts (around 10kHz)
- weak, almost continuous $n = 4$ activity (around 30kHz)

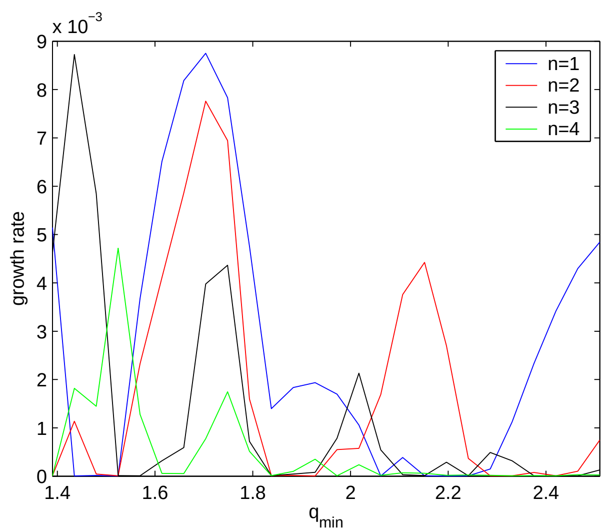

Figure 2: Stability of the hollow current profile for different values of q_{min} and for the first four principal modes

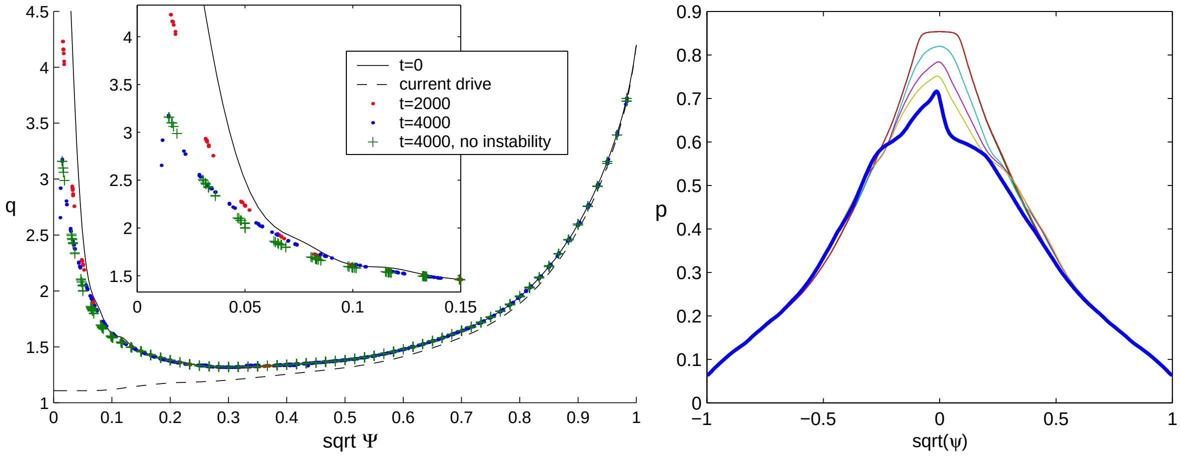

Figure 3: Non-linear evolution of the infernal mode. [left] Safety factor profiles showing that the infernal mode has no effect on the safety factor. Time is given in Alfvén units [right] Pressure profiles showing a strong pressure drop as the infernal mode saturates.

- a late (after 7s) moderate $n = 2$ activity (10-15kHz).

Assuming the interchange modes found numerically would show up on the magnetic acquistion system, measurements and numerics are consistent for a minimal value of the safety factor around 1.5, where no $n = 3$ mode is present (see fig. 2).

A second linear investigation was performed numerically using XTOR [10] for resistive, full MHD simulations including transport and bootstrap current, and without X-point. Here, the Lundquist number is $S = 2.10^6$ and the transport coefficients (normalized) are $\chi_{||} = 2.10^3$, $\chi_\perp = 2.10^{-5}$ in order the keep $\chi_{||}/\chi_\perp = 10^8$ and $S\chi_\perp \sim 150$ as in the experiment. This has been done for both the original and the regularized profile. In addition to the previous resistive interchange, which is much less unstable here, we find a $n = 3$ infernal mode which develops quickly for values of q_{min} close to $4/3$ as it will be further discussed in next section (see also fig. 3 and 4).

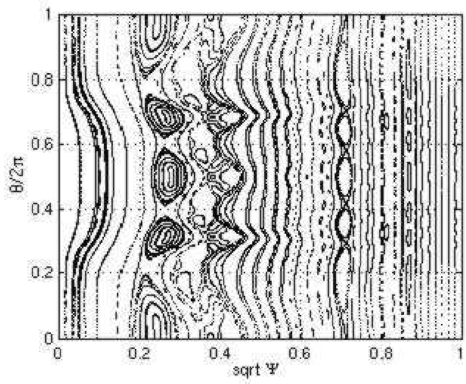

Figure 4: Poincare plot of the saturated $n = 3$ infernal mode (pressure driven) for the JET shot #66498, with $q_{min} = 1.31$, triangularity $\delta = 0.3$, and $q_{95} \sim 5$

Non-linear dynamics

In order to test the ability of the infernal mode to fill the hollow current profile, we use XTOR with the flat current profile as current source, and the original current profile as initial current with $S = 5.10^6$. When the instability saturates, the pressure drops in the central region, and there is also current redistribution. The Poincaré plot (fig. 4) shows the magnetic islands and also a slight shift of the magnetic axis.

To ditinguish the effects of the infernal mode from current diffusion alone, we ran another simulation without $n = 3$. The evolution of the safety factor was the same, showing that the infernal mode affects almost only the pressure profile (fig. 3). This means also that current redistribution does only occur in directions other than radial.

The infernal mode is thus not responsible for the filling of the hollow current profile, and its developement does not lead to a crash, but rather to a considerable pressure drop.

Discussion

In the described experiment, the hollow current profile is not a steady state feature. Since the plasma current is not fully driven by non-inductive current sources, current diffusion alone would fill the NCS region slowly, but MHD instabilities may fill it even more quickly. In fact, during the pulse, the safety factor near the magnetic axis decreases faster according to experimental data than in the CRONOS simulation. This suggests that an MHD instability is at work.

The present study shows that the infernal mode has almost no effect on the safety factor profile, but results in dramatic pressure drops. Other MHD modes may affect the current hole : previous studies showed that the resistive interchange mode flattens the safety factor profile in the NCS region [4] and that the resistive kink prevents a negative current to appear [5]. However, resistive interchange is quite challenging to simulate and is still work in progress.

Acknowledgement

Many thanks to J.F. Artaud and F. Imbeaux for their support on running CRONOS simulations, and X. Litaudon for fruitful discussions.

References

[1] T.S. Taylor, *Plasma Phys. Control. Fusion* **39** B47 (1997)
[2] X. Litaudon, *Plasma Phys. Control. Fusion* **40** A251 (1998)
[3] T C Hender et al, *Plasma Phys. Control. Fusion* **44** (2002)
[4] M. S. Chu et al, *Phys. Rev. Letters* **77**, 2710 (1996)
[5] G. T. A. Huysmans et al, *Phys. Rev. Letters* **87**, 245002 (2001)
[6] X. Litaudon et al, *IAEA Chengdu* EX/P1-12 (2006)
[7] We acknowledge M. Brix and N. Hawkes for MSE q-profile determination.
[8] V. Basiuk et al, *Nuclear Fusion* **43** 822 (2003)
[9] W. Kerner et al, *J. Comp. Phys.* **142** (1998)
[10] K. Lerbinger and J.-F. Luciani, *J. Comp. Phys.* **97**, 444 (1991)