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q-profile evolution and improved core electron confinement in the full current drive operation on Tore Supra

X. Litaudon, Y. Peysson, T. Aniel, G. Huysmans, F. Imbeaux, E. Joffrin, J. Lasalle, P. Lotte, B. Schunke, J.L. Segui, G. Tresset, M. Zabiego

Association Euratom-CEA, DRFC, CE Cadarache,13108 Saint-Paul-Lez-Durance, France.

Introduction

Recent improved confinement experiments with significant current profile modification in full current drive Tore Supra operation are described in this paper together with their detailed modelling. Lower Hybrid (LH) plasma driven discharges have been realised during the 1999 experimental campaign : (i) to assess the behaviour of a recently designed and installed LH antenna in this operation mode [1-2], and (ii) to further determine the link between the LH power deposition, the q-profile evolution and the core electron confinement. Indeed, since the previous full current drive experiments [3-4], a new hard x-ray (HXR) tomography system with a high spatial resolution in the plasma core (4-5cm) has been installed on Tore Supra [1,5]. This diagnostic is well designed for an accurate determination of the LH power deposition and current profiles dynamics in the zero-loop voltage regime where current density and pressure profiles are fully decoupled. The main experimental conditions and results are first briefly reported in the first section. Then, the emphasis is laid on the analysis of the current profile evolution towards a steady-state equilibrium. In the second section, we report the self-consistent predictive electron transport modelling of discharges characterised by either the absence or the occurrence of a spontaneous central electron temperature transition.

1) Description of the experimental scenarios and current diffusion analysis

Using a “constant-flux” feedback scheme [4], fully non-inductive plasmas have been obtained during the 1999 experimental campaign in a reproducible and systematic manner in a regime where most of the non-inductive current is driven by the Lower Hybrid (LH) waves (n_{eo}=2.5$10^{19}$m^{-3}, B_t=3.9T, I_p=0.7-0.8MA, P_{LH} =4-4.7MW). Up to 4.7MW of LH power has been coupled during up to 10s while the loop voltage was prescribed exactly to zero.

In this regime, we have simulated the resistive current profile evolution of a set of discharges where the parallel index at the peak of the launched spectrum, $n_{//O}$, has been varied between 1.65 and 2.3. The code CRONOS [6] is used to analyse the diffusion of the electric field inside the plasma and to assess the evolution of the current profile with different antenna phasing. The LH power is applied on steady ohmic plasma characterised by a weak sawtoothing activity inside r/a =0.15; this information is used together with the measured value of internal inductance, l_i, and total plasma current to constrain the initial q-profile taken in the code as initial condition. Then to simulate the q-profile evolution after the application of the additional power, the LH power deposition and current profiles have been directly scaled from the radial hard x-ray emission profiles deduced from the new HXR tomography system [5]. The scaling factors are respectively fixed by the total LH power and the LH current drive efficiency of the order of 0.6$10^{19}$m^{-2}A/W. The non-inductive sources are the LH and bootstrap currents and they add up to provide the total plasma current. A complete current diffusion analysis is presented for a stable, steady-state discharge with $n_{//O}$=1.8. As shown on Fig. 1 (left) the measured data (magnetic loops, internal inductance and polarimetry) are well reproduced which provides a reasonable assessment of the current profile evolution. The current diffusion analysis shows that the electric field becomes stationary within a time of the order of 2s and the bootstrap current is of the order of 10%. In this precise case, q-on axis (q_o) rises above one and a steady q-profile is reached with q_o below two with a narrow region of weak or slightly negative magnetic shear (Fig. 1 (right)).

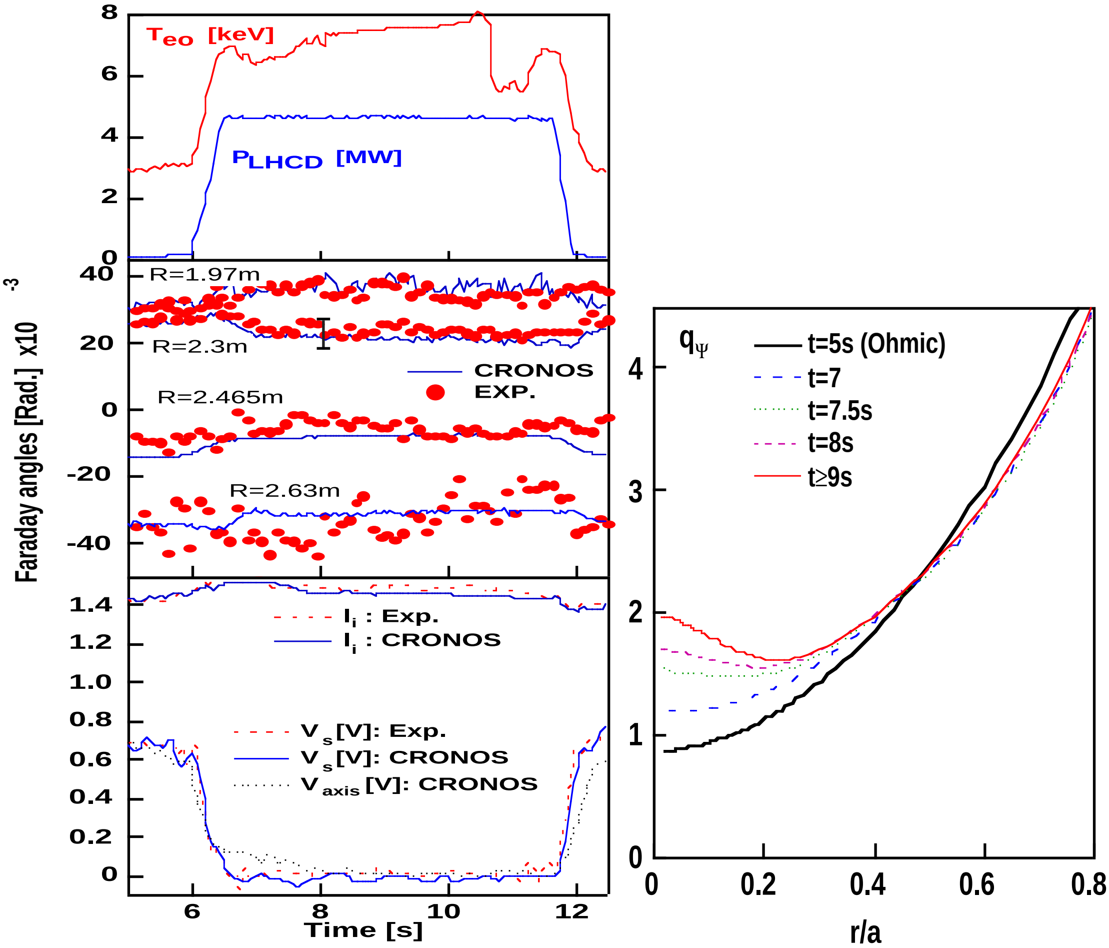

Fig. 1: *Resistive current diffusion simulation (CRONOS) using the experimental hard x-ray profiles for the LH current profiles (#28342 with $n_{//O}$=1.8); (left) Time evolution of T_{eo}, LH power, experimental and simulated Faraday rotation angles, l_i and loop voltage; (right) q-profile evolution (CRONOS) towards a fully non-inductive plasma state.*

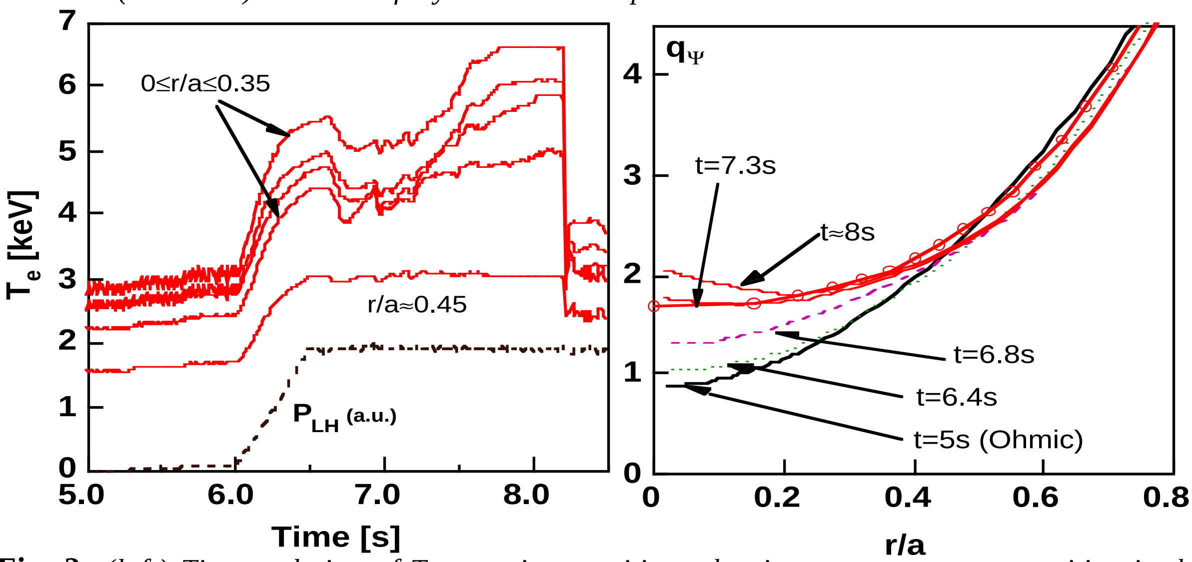

Fig. 2: *(left) Time evolution of T_e at various positions showing a spontaneous transition in the plasma core at t≈7.3s and a collapse at t≈8.2s (P_{LH}=4MW); (right) Simulated q-profile evolution (CRONOS) using the hard x-ray profiles; the open circles correspond to the q-profile deduced from the equilibrium reconstruction code (IDENT-D) (#28334 compound spectra $n_{//O}$=1.65/2.3).*

By varying the antenna phasing slightly different q-profiles have been obtained when the electric field profile is close to zero. Indeed, with a higher $n_{//O}$ ($n_{//O}$≈2) the region with weak magnetic shear is extended up to r/a=0.3 with the minimum q value close to two. Detailed evolution of the electron temperature and simulated q-profiles is illustrated on Fig. 2. About 0.4s after the LH power is applied, the current diffusion analysis indicates that q_o rises above one in agreement with the rapid stabilisation of the sawtooth activity. Then, about 1.3s (t=7.3s) after the LH power is turned on, the central temperature, T_{eo}, shows a transition to an improved core confinement phase, when T_{eo} rises from 4.5keV up to 6.5keV. The spontaneous T_{eo} transition occurs when the magnetic shear is reduced close to zero in the plasma core (Fig 2 (right)). These transitions are considered as a bifurcation of confinement since during the transition the hard x-profiles are constant (cf. section 2) [1]. Finally less then one second after the T_{eo} transition, MHD activity is triggered when the minimum q-value approaches two. This sharp MHD transition (collapse of T_e in less than 100µs) appears as a global resistive mode extending over the core region inside the q=2 surface. The simulated q-profile evolution is in agreement with the MHD analysis of the temperature collapse.

2) Predictive modelling of improved core electron confinement

For the predictive simulations we have used the mixed Bohm and gyro-Bohm electron transport model which has been successful in simulating various regimes in JET [7, 8] and Tore Supra [9-10]. To link the electron heat diffusivity, χ_e, to the magnetic shear, the Bohm term is reduced in the region of weak or negative magnetic shear [11]. Simulations have been performed with the CRONOS code in which the coupled heat and current transport equations are evolved self-consistently using the shape of the measured HX profiles for the LH power and current profiles. Fig. 3 shows the predictive time evolution of T_{eo} by including or not the magnetic shear correction in the transport model. The increase of T_e(r/a) is correctly simulated because of the reduction of χ_e inside r/a≤0.35. Indeed, when the magnetic shear is reduced in the plasma core, χ_e self-consistently decreases from typically 1.5m^2/s down to 0.6m^2/s to recover the ohmic level despite the application of 4.6MW of LHCD power. The power deposition profiles, measured by the HXR-tomography system, are broad and centered at r/a=0.3 and do not evolve when the electron temperature profiles peak in the core

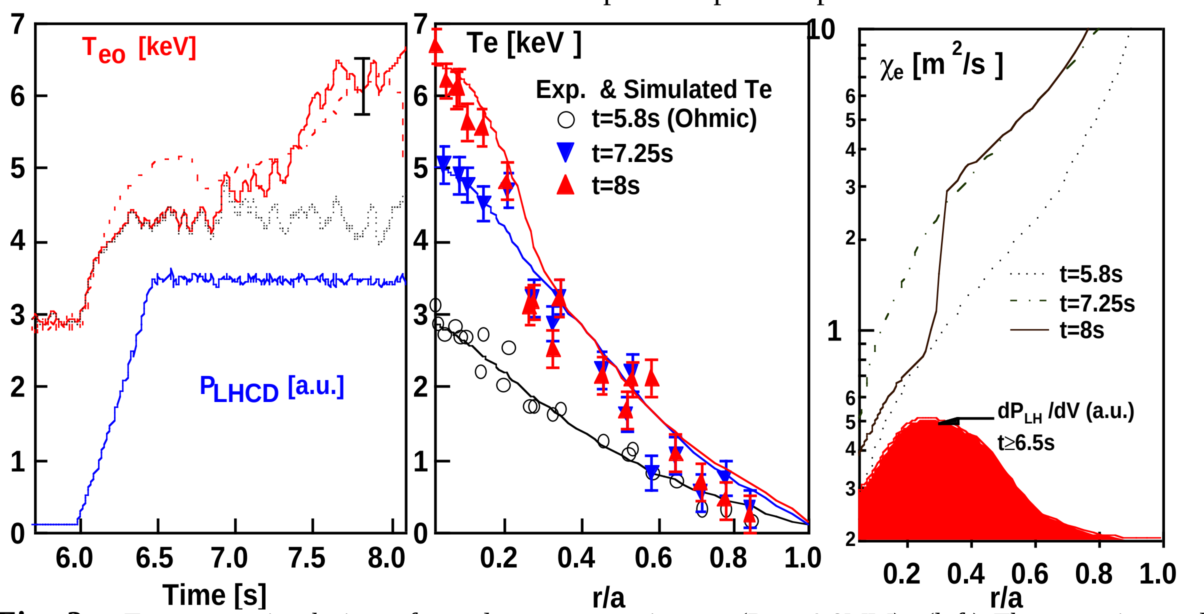

Fig. 3 : *Transport simulation of steady-state experiments (P_{LH}=4.6MW): (left) The experimental (dashed line) and the simulated (full line) time evolution of T_{eo}. The dotted line corresponds to a simulation performed without including the magnetic shear dependence in the transport model. (middle) The experimental and simulated T_e profiles (full lines). (right) The corresponding χ_e profiles and the measured power deposition profile. (#28348 compound spectra $n_{//O}$=1.8/2.3).*

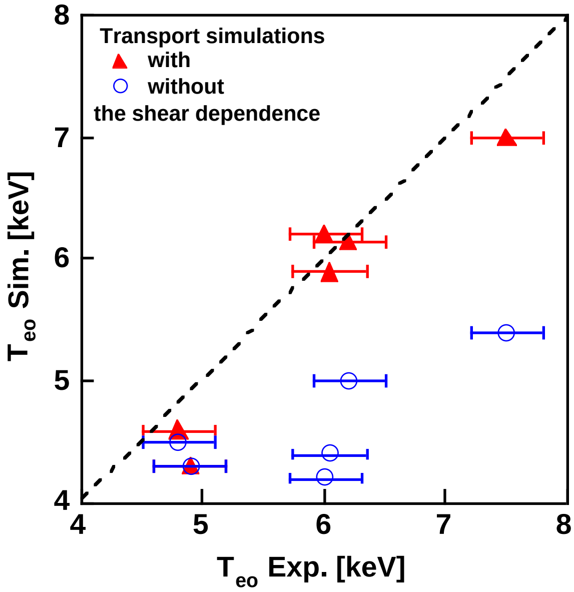

Fig. 4 : *Simulated T_{eo} (CRONOS) versus the experimental values. Each point corresponds to one pulse of the $n_{//0}$ scan. The dark triangles (respectively the open circles) correspond to the transport simulations performed with (respectively without) the magnetic shear dependence in the transport*

Similar predictive transport modelling has been performed for a large number of zero-loop voltage discharges where the LH antenna phasing has been varied, i.e. corresponding to various formations of q-profiles with monotonic or non-monotonic shapes. The results of the simulations are summarised in Fig.4 where the simulated core temperatures have been plotted versus their experimental counter-parts for each pulse. A better agreement with the experimental data is obtained when the magnetic shear dependence is included in our modelling, in particular to reproduce the phase when the electron temperature profiles peak in the plasma core ($T_{eo} \geq 5$keV in Fig. 4). For discharges with monotonic q-profiles where T_{eo} transitions are not observed, the simulations with or without the magnetic shear correction give similar results.

Conclusion

Current diffusion and local transport analyses using the most accurate experimental determination of the LH current and power deposition profiles provided by the HXR tomography system of Tore Supra, show that the core temperature transitions should be interpreted as a reduction of the anomalous electron transport. The electron thermal diffusivity, χ_e, is reduced from the Bohm to the gyro-Bohm level [7] (from 1-2m^2/s down to 0.4-0.5m^2/s) in the weak magnetic shear region. In the predictive transport modelling, the non-linear coupling between the magnetic shear and χ_e should be taken into account to reproduce the emergence of different thermal states during the current profile evolution towards a genuine steady-state equilibrium. The future challenge for steady-state operation of Tore Supra consists in the extension of the region with a weak magnetic shear at higher density and bootstrap current fraction while avoiding the occurrence of sudden pressure collapses at the vicinity of low order rational q-surfaces (e.g. q=2) [12].

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