

EDGE COOLING EXPERIMENTS AND NON LOCAL TRANSPORT PHENOMENA IN TORE SUPRA

X.L. Zou, M. Erba, A. Géraud, P. Gomez, M. Mattioli, J.L. Ségui, F. Clairet, C. De Michelis,
P. Devynck, T. Dudok de Wit ^a, C. Fenzi, X. Garbet, C. Gil, P. Hennequin ^b, F. Imbeaux,
E. Joffrin, G. Leclert ^c, A.L. Pecquet, Y. Peysson, R. Sabot, T.F. Seak

Association Euratom-CEA, DRFC, CEA Cadarache, 13108 Saint Paul lez Durance, France

^a *Centre de Physique Théorique Luminy, case 907, F - 13288 MARSEILLE Cedex 9, France*

^b *Laboratoire PMI (UPR 287 du CNRS), Ecole Polytechnique, 91128 Palaiseau, France*

^c *Laboratoire de Physique des Milieux Ionisés, ESA CNRS 7040, Université Henri Poincaré,
Nancy, BP 239, 54506 Vandoeuvre Cedex, France*

1. Introduction

In the stationary regime it has been shown that the electron transport is gyro-Bohm *i.e.* the correlation length is much shorter than the plasma size, and the associated is electromagnetic [1]. This gyro-Bohm behaviour has been confirmed by density fluctuation measurements. The electromagnetic nature of the transport is on the other hand corroborated by the magnetic fluctuation measurements and a good agreement has been found between the experimental heat flux and that estimated from magnetic fluctuations [2]. Thus the features of electron transport in stationary regimes are diffusive, electromagnetic, with short correlation length compared to the plasma size. However in transient regimes, the electron transport is not always compatible with a simple diffusive model, since large scale transport events are observed with a propagation time smaller than a diffusion time. Recently a new phenomenon of non local transport (NLT) has been evidenced in TEXT [3] and TFTR [4] in perturbative heat transport experiments, and is described by a simple and controversial picture : a strong cooling in the edge plasma provokes a notable heating in the central plasma core within a time much smaller than a diffusion time. This non-diffusive, long-range and reversed polarity response due to an edge temperature perturbation raises the basic problem of locality for the "standard" (local and turbulent) transport model. Investigating the mechanism behind this new phenomenon presents a great interest for the understanding of transport mechanism which remains an open issue in tokamaks.

2. Ohmic regimes

Edge cooling experiments have been performed in Tore Supra by three different methods : oblique pellet injection, impurity injection (Ni, Mn) by laser ablation and gas injection (Neon or Argon). The electron temperature perturbations are measured with a multichannel electron cyclotron emission (ECE) heterodyne system. The plasma density is measured with a multichord interferometer. For all the experiments presented in this paper, the major and minor radii are respectively $R = 2.31 m$, $a = 0.75 m$, the magnetic field is $B = 3.7 T$. The plasma current is $I_p = 0.6 - 1.5 MA$, and the line average density range is $\bar{n}_e = (1 - 3) \times 10^{19} m^{-3}$. Results obtained with impurity injection are very similar to that reported in TEXT [3] and in TFTR [4], where a significant temperature increase has been observed in the central core during the impurity injection, and the reaction time of the plasma centre to the edge perturbation is less than 1 ms, much smaller than the heat diffusion time. The non local transport features (drop at the edge and rise in the centre for T_e) have also been confirmed in the ohmic regime with pellet injections. Fig.1a displays the electron temperature response to a pellet injection. A positive perturbation of 0.7 keV has been reached for the temperature measured close to the rational surface $q = 1$. This result is similar to that reported in JIPPT-IIU [5] and in RTP [6]. Without special mention, the experiments presented in the following are carried out with pellet injection. Note that the pellet velocity is $V_p \approx 500 m/s$ and the minimum radius reached by the pellet in the oblique configuration is typically $r/a \approx 0.65$. More technical informations on this pellet injection configuration can be found in [7].

The non local transport effect in Tore Supra occurs at low density and high temperature (or plasma current), and these results are similar to those reported in [4]. Fig.1b presents the diagram of the temperature response to the edge cooling. A threshold on the line average density \bar{n}_e and current I_p is clearly observed from this figure: $\bar{n}_e / I_p^{1/2} \leq 1.0 \times 10^{16} (m^{-3} A^{-1/2})$. Furthermore a second threshold on the relative density variation caused by the pellet injection has also been observed: $\Delta \bar{n}_e / \bar{n}_e \leq 0.5$. The second threshold probably expresses the pellet ablation localisation effect. Indeed the larger the pellet size and the deeper the pellet penetration.

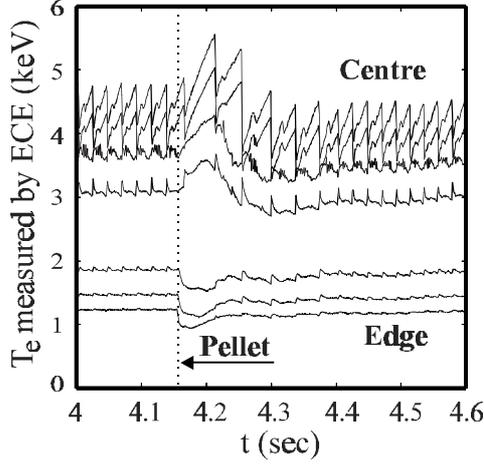


Fig.1a Response of the electron temperature (ECE) to a pellet injection in the OH regime.

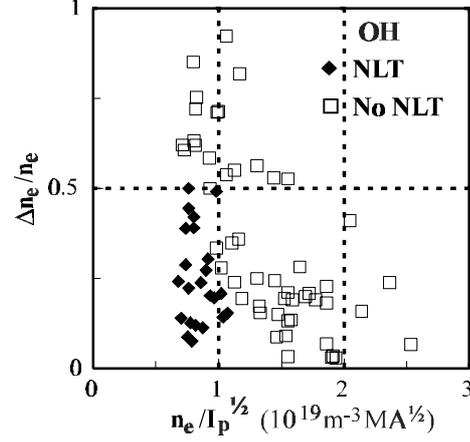


Fig.1b Diagram for the non local transport with pellet injection. ◆ (□) corresponds to the case where a temperature rise in the core is (not) observed.

3. LH regimes

Edge cooling experiments have also been carried out in the L regime with Lower-Hybrid (LH) wave heating. Significant enhancements have been found for the non local transport effect in this regime when compared to the ohmic regime. We emphasise that these results differ from those obtained in TFTR and TEXT, where the non local effect tends to disappear with additional heating (NBI, ECRH). In Tore Supra besides the heating effect, the extensive use of lower-hybrid wave especially aims to control the non-inductive current density profile by creating fast electrons. These fast or suprathermal electrons can then strongly affect the ECE signals in the very low density range with a central density $n_{e0} \leq 2.5 \times 10^{19} m^{-3}$. In Tore Supra the suprathermal electrons are measured by using a tomographic system of hard x-ray (**HXR**) emission between 20 and 200 keV [8]. With the presence of suprathermal electrons, the ECE signal results from two additive contributions, one from the thermal electrons and another one from the suprathermal electrons. In order to determine whether the core temperature increase is thermal, the influence of the suprathermal electrons on the ECE measurement has to be investigated. Fig.2a shows an example with injection of two pellets, which allows to discriminate the suprathermal electron effect. During the large (first) pellet injection, preceding the rise, a sudden drop has been observed on the ECE signals measured in the central core, while no drop has been observed during the small (second) pellet injection. As shown in Fig.2a the HXR signal of a central chord are strongly affected by the large pellet injection, but not by the small pellet injection. On the other hand, the characteristic time of the HXR signal drop at the centre is about 25 ms, which is compatible with that of the ECE signal drop. These indicate that the ECE signal drop is likely due to the suprathermal part and the ECE signal increase is due to the thermal part. Thus this drop does not question the non local phenomenon. A simulation of the ECE has shown that the ECE signals are affected by the suprathermal electrons not only at the edge ($r/a > 0.8$) (strongly), but also in the plasma centre (less), while it is not affected in the temperature gradient region. This explains very well why only the ECE signals measured in the centre have undergone a drop.

As in the ohmic case, figure 2b displays the non local transport diagram. Compared to the previous case, the limit on $\bar{n}_e / I_p^{1/2}$ is now extended : $\left[\bar{n}_e / I_p^{1/2} \right]_{crit} = 1.4 \times 10^{16} (m^{-3} A^{-1/2})$, and no limit has been now observed for $\Delta\bar{n}_e / \bar{n}_e$ in LH regimes. The latter is doubtless resulting from the suprathermal electrons at the plasma edge. Indeed large relative density variation $\Delta\bar{n}_e / \bar{n}_e$ can not be reached in this case due to the reduced pellet fuelling efficiency, which is directly linked to the more peripheral pellet penetration caused by suprathermal electrons. Note that in this L regime, the non local feature has also been observed with gas injection, while in the ohmic case the result is uncertain.

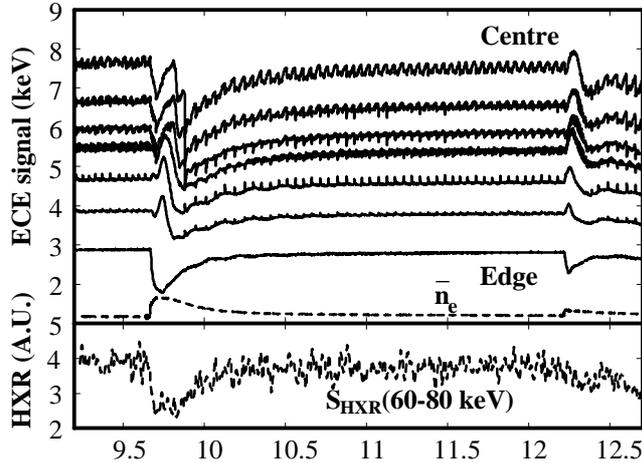


Fig.2a Response of the electron temperature (ECE) for two pellet injections in the LH regime. \bar{n}_e is the line average density and the HXR signal is also displayed.

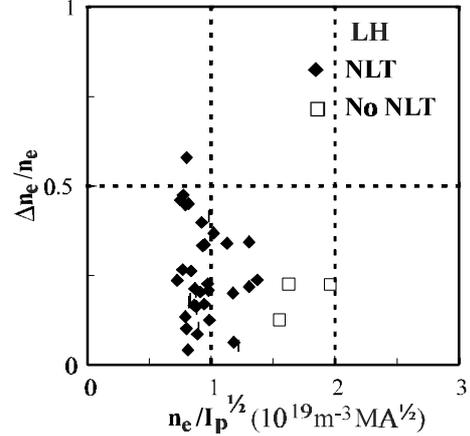


Fig.2b Diagram for the non local transport with pellet injection in the LH regime. \blacklozenge (\square) corresponds to the case where a temperature rise in the core is (not) observed.

4. Discussions and interpretations

In these experiments, the challenge is to identify the mechanism governing the non local transport. An ensemble of candidates could include the current profile redistribution, the magnetic shear, the toroidal coupling of low- m magnetic fluctuations, the plasma rotation shear or radial electric field, *etc.* In the present experiments, no evident proof exists to determine which is responsible for transmitting the non local response. However there are some indications which can exclude some potential candidates.

Figure 3 presents a pellet edge cooling experiment in the full non-inductive current regime with LH wave, where the ohmic plasma current is fully replaced by a non-inductive current carried by the suprathermal electrons. In figure 3a the non local transport feature is obvious : in consequence of the peripheral pellet injection, a positive temperature perturbation is created in the region close to $r/a = 0.44$, then this hot pulse propagates "classically" toward the centre with a characteristic time (≈ 40 ms) compatible with the diffusion time. This picture let suggest that an internal transport barrier is immediately constituted after a strong edge cooling, this barrier stops on one hand the inward propagation of the cold pulse, and on the other hand the outward heat diffusion, then this barrier shifts slowly toward the centre. This indicates that both local and global transport features exist simultaneously in the tokamak plasma, and the appearance of this non local feature depends on the perturbation form or rather a hidden parameter. During this injection the sawtooth activity has been totally suppressed as shown in Fig.3a, where no trace of sawtooth is perceptible on the ECE signals. Furthermore, as shown in figure 3b there is no variation during this pellet injection for the loop voltage V_{loop} , the radiation power P_{rad} , the input LH power P_{LH} and the HXR signals for a central chord at two different energy channels, which are a measurement of the non-inductive current level. And lastly no excitation of low- m MHD modes has been observed contrary to that reported in TFTR. These observations indicate clearly that the mechanism governing the non local transport is not correlated with a change of the current profile, and the role of low- m MHD in the mechanism for NLT is unlikely. Note that the characteristic time of the current change is much slower than that observed in the NLT phenomenon. In conclusion mechanisms based on spatial redistribution of the plasma current, or

modification of the magnetic shear, could be excluded for the non local transport. However some arguments seem to show that the NLT phenomenon can be linked to the plasma rotation (the radial electric field). Indeed the plasma rotation is higher in LH regimes, which is consistent with the enhancement of the NLT effect in LH regimes. In addition MHD modes are slowing down during the pellet injection. All these suggestions need to be confirmed with further experiments.

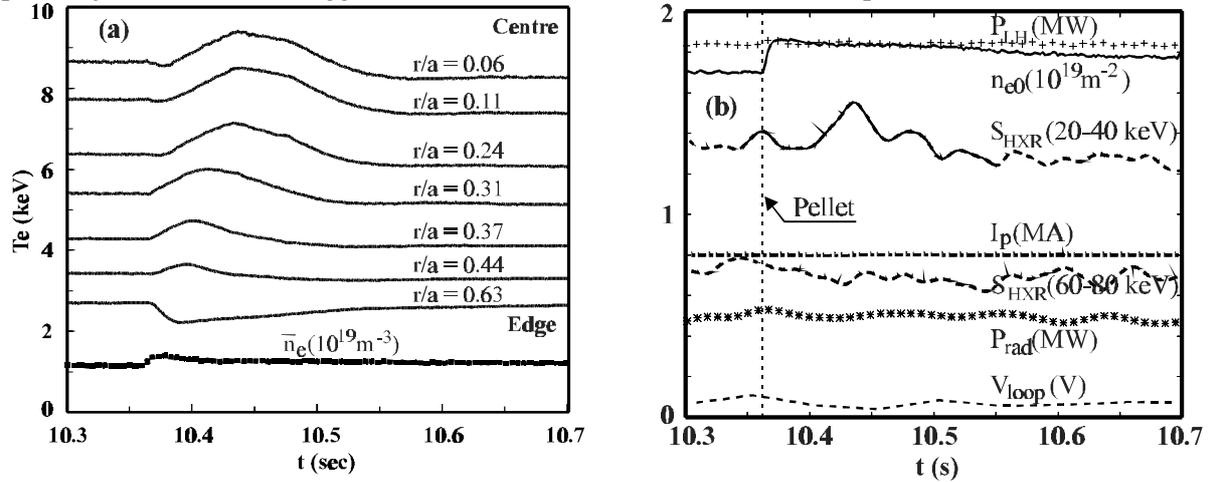


Fig.3 Pellet injection experiment in the full non-inductive current regime with LH wave. (a) ECE temperature response and the line average density \bar{n}_e . (b) Time evolution of the current I_p , the central density n_{e0} , the LH input power P_{LH} , the total radiation power P_{rad} , the loop voltage V_{loop} and the HXR signals (A.U.).

5. Conclusions

The edge cooling experiments in Tore Supra have reproduced the robust non local transport phenomenon in ohmic regimes, and some original results have been obtained in LH regimes. In ohmic regimes, the existence of a threshold on the plasma density and current has been confirmed. A second threshold on the relative density variation caused by the pellet injection has also been obtained. In the L regime with LH heating, significant enhancements have been found for the non local feature when compared to the ohmic regime, the operation domain on density is now extended, and no limit has been observed for the pellet size. Some experimental observations seems to suggest that the mechanism governing the non local transport is unlikely linked to the current effects including the spatial redistribution and the magnetic shear, and the low- m MHD modes. It is not excluded that the plasma rotation could contribute to this effect by creating a internal transport barrier.

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