*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-4.209 (2009)*

Influence of the electron temperature gradient on impurity transport in Tore Supra

D. Villegas, R. Guirlet, C. Bourdelle, X. Garbet, F. Imbeaux, J.-L. Ségui, R. Sabot.

CEA, IRFM, F-13108 St-Paul-lez-Durance, France

Introduction

Impurity transport in the plasma core of a tokamak is a crucial issue for a future fusion device like ITER. In most experimental situations, impurity transport cannot be explained by neoclassical (i.e. collisional) effects alone [1]. Turbulence should be taken into account to explain this observed anomalous transport. Theoretical models predict that turbulence is highly sensitive to the electron temperature gradient $\nabla T_e/T_e$ [2]. In this paper we report on an experimental test of the effect of $\nabla T_e/T_e$ by means of local modification during a series of Tore Supra discharges where heavy impurities are injected as traces. The results are compared to neoclassical and gyrokinetic predictions.

Experimental configuration

We have performed a series of Tore Supra discharges in deuterium. The main parameters are the following: major radius R_0 = 2.35m, minor radius a = 0.72m, toroidal field B_T = 3.78T, plasma current I_p = 0.5MA, safety factor at the last close surface q_ψ = 10.05. The central electron density is $n_e(0) = 3.3 \times 10^{19} m^{-3}$ and central electron temperature is $T_e(0)$ = 1.8keV. The discharges are virtually (ohmic case) or completely (other three cases) sawtooth-free. The electron density is measured by two reflectometers (with 1cm spatial resolution and time resolution between 4 and 8 ms) and a 10-chord interferometer. The electron temperature is measured by an ECE radiometer with 32 channels (2.5cm spatial resolution and 1ms time resolution) (Fig. 1). The electron temperature profile is changed by adding 300kW of Electron Cyclotron Heating (ECH) of two gyrotrons either at r/a = 0.35 or at r/a = 0.58.

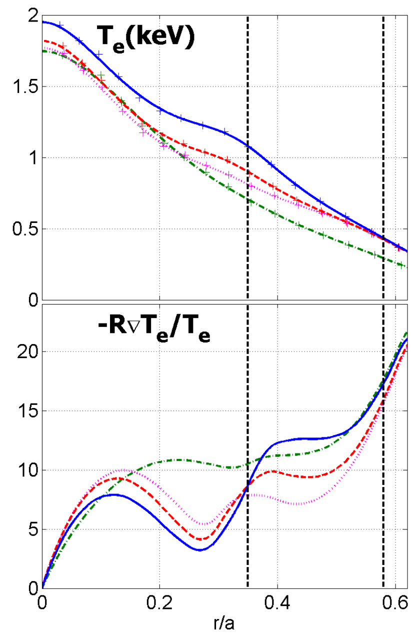

Figure 1: electron temperature profile and its gradient. (line : TS#40801, dashed : TS#40805, dotted : TS#40807, dash-dot : TS#40798)

The impurities to be studied, nickel (Z = 28) and germanium (Z = 32), are injected as traces by a laser blow-off system described in [3]. The behaviour of impurities is observed with a VUV spectrometer and two soft-X-ray cameras with a 2ms time resolution. To obtain an estimation of the impurity quantity injected, we used a bolometer array which is calibrated in physical units. The following table summarizes the power deposition radius of the four shots analyzed and the impurity injected:

	Gyrotron 1	**Gyrotron 2**	**Impurity**
40798	Ohmic shot		Ge
40801	r/a = 0.35	r/a = 0.35	Ni
40805	r/a = 0.58	r/a = 0.35	Ni
40807	r/a = 0.58	r/a = 0.58	Ni

Measurement analysis

The injected impurity soft-X-ray emission is analyzed in simple terms (Fig. 2a and 2b). We compute the time-width at mid-height of each chord of the horizontal soft-X-ray signals (Fig. 2c). The green curve represents the ohmic shot. It shows a flat time-width compared to those which correspond to shots with ECH. With the usual assumption of a diffusive-convective flux, this uniform time evolution of the soft-x-ray can be explained for example by a rather flat diffusion profile in the ohmic case. On the contrary, the peaked time-width profile in the central ECH case is indicative of a lower diffusion coefficient at the plasma centre than in the periphery. Consistently, the intermediate cases of outer and mixed deposition locations exhibit a moderate peaking.

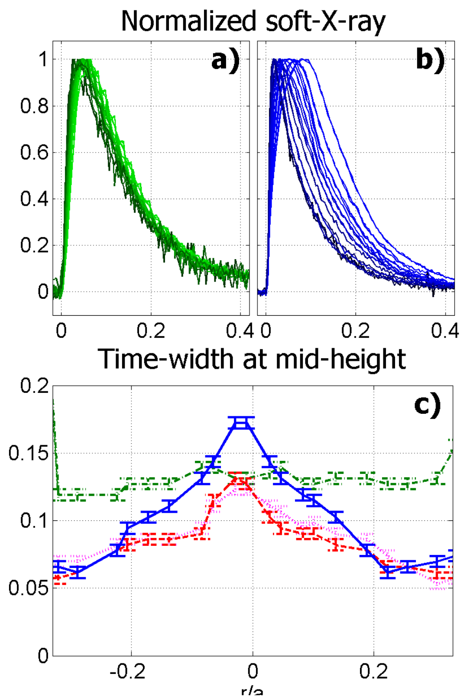

Figure 2: Time evolution of normalized soft-X-ray signals: a) TS#40798, b) TS#40801. c) Time-width at mid-height for all shots

Radial transport analysis

As usual, the radial flux of impurities is modelled as a sum of a diffusive term and a convective term where D and V are assumed to be time independent:

$$\Gamma_Z = -D\nabla_r n_Z + V n_Z$$

We use the ITC code [3] to solve the system of continuity equations for all the ionization states of the injected impurity [3] :

$$\frac{\partial n_Z}{\partial t} + \nabla\Gamma_Z = S_{Z-1} + R_{Z+1} - \left(S_Z + R_Z\right) + s_{ext}$$

where S_Z and R_Z represent the ionization and the recombination rates of the ionization stage Z respectively, and s_{ext} is the external source of impurities. Various techniques are used to adjust the D and V profiles for the simulated signals to match as well as possible the measurements. Recently a genetic algorithm has been implemented in ITC to improve the determination of D and V profiles. It should increase the accuracy of the D determination and avoid as much as possible local minimum values of a chi square χ^2 which quantifies the difference between measurements and simulation. Fig. 3 shows the D and V profiles for the four cases. The uncertainties have been obtained by selecting all profiles homothetic to the best one and characterised by $\chi^2 \leq 1.33\chi^2_{\min}$. The results confirm that in the ohmic case (green) the D profile is flat as suggested above. Moreover, the central diffusion coefficient is higher. On the contrary, adding ECH leads to a reduced diffusion in the plasma centre (D ~ 0.01m^2/s for the central deposition case), which is consistent with the long time-width of central soft-X-ray emission. As it is shown in figure 4, the lower the temperature gradient, the more the diffusion coefficient is reduced. This dependence also suggests the proximity of the $\nabla T_e/T_e$ threshold. For r/a > 0.3, the diffusion profiles of all ECH shots are very similar and diffusion increases up to the plasma edge. As already noticed for this technique [4], the determination of the convection velocity yields larger uncertainties. However for all shots, V is negative which corresponds to inward convection everywhere in the plasma. Furthermore, we notice that convection in the inner part of the plasma is reduced in the ECH cases, which, associated with a small diffusion, could be explained by a reduction of central turbulence due to flattened profiles.

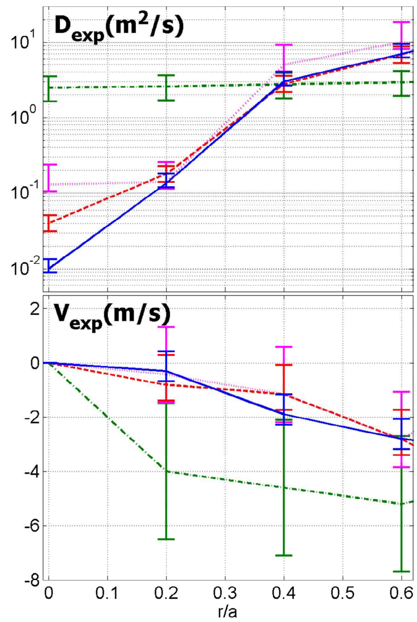

Figure 3: Experimental D and V profiles

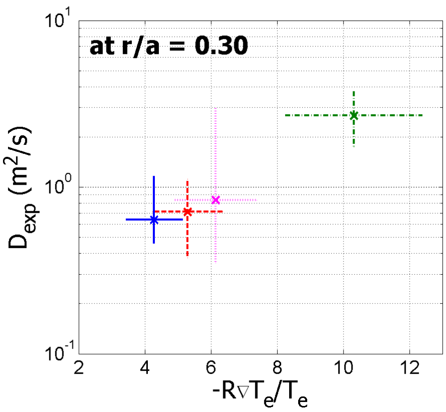

Figure 4: Experimental D versus $\nabla T_e/T_e$ at r/a = 0.3

Neoclassical and turbulent transport modelling

We use the NCLASS code, to evaluate the neoclassical diffusion coefficient and convection velocity profiles (Fig 5). The input data to NCLASS are based on fits of the measured profiles and q profile estimation computed by current diffusion with the CRONOS code [5]. In the plasma centre (r/a < 0.2), experimental diffusion for ECH shots has the same order of magnitude as the neoclassical prediction, but elsewhere it is anomalous.

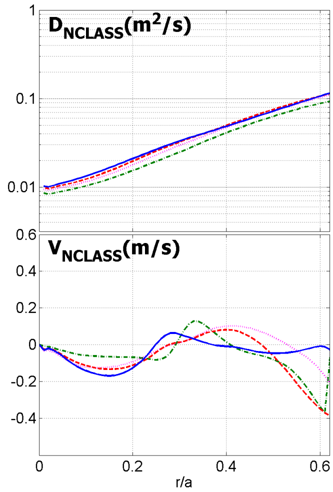

Figure 5: Neoclassical D and V profiles

Hence, outside r/a = 0.2, we perform quasilinear gyrokinetic simulations with QuaLiKiz [2] to compare our observations with turbulent transport modelling. This code computes a diffusion coefficient and the two terms of the convection velocity, compressibility-curvature and thermodiffusion (Fig 6). We present here the results on the ohmic shot (in green) and the central ECH deposition case which has the lowest $\nabla T_e/T_e$, assuming T_i homothetic to T_e due to lack of T_i profiles measurements. Inside r/a = 0.3 the predicted turbulent diffusion in the ECH case is lower than in the ohmic shot due to a flattening of the temperature profile. Furthermore, thermodiffusion is outward, as expected with a turbulence drifting in the ion diamagnetic direction. But since the thermodiffusion scales as 1/Z, the curvature term is hugely dominant and inward at all radii, which is consistent with experimental observations. The simulation also confirms that in the ECH case, convection velocity is reduced in the plasma centre.

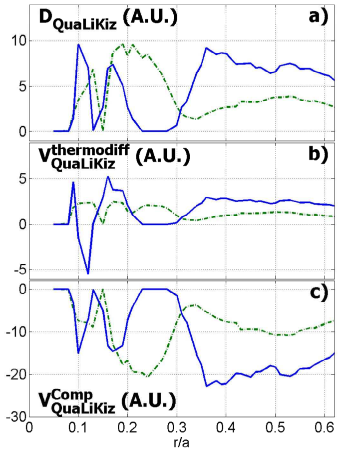

Figure 6: a) Diffusion coefficient, b) compression velocity, c) thermo-diffusion velocity from

Conclusion

Impurity transport has been studied in plasmas where the temperature gradient was changed by adding ECH. For these EC heated shots, experimental analysis reveals, for r/a < 0.2, the existence of a decrease of diffusion coefficient with lower $\nabla T_e/T_e$. Consistently, turbulent transport theoretical predictions show that decreasing the temperature gradient leads to reduced transport coefficient down to neoclassical level.

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