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Anomalous Transport of Light and Heavy Impurities in Tore Supra Sawtooth-free Ohmic Plasmas

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Introduction : Impurity transport in fusion devices plays a crucial role both in the plasma core performances and in its capacity to maximise the radiated part of its power losses. In most experimental situations impurity transport is dominated by phenomena other than collisional (the so-called *neoclassical*) transport [1]. It is often asserted that turbulence is responsible for this observed anomalous transport. However, the turbulent transport models still lack experimental confirmations [2, 3]. In the present publication we suggest improvements to the experimental method and we pursue [4] a comparison between experiments and models by investigating the ohmic, sawtooth-free plasma situation over an extended impurity charge range.

Experimental scenario and measurements: We have performed a series of ohmic discharges: major radius R_0 = 2.38 m, minor radius a = 0.72 m, plasma current I_p = 0.5 MA, toroidal field B_T = 3.87 T and safety factor at the last closed flux surface q_ψ = 9.75. The central electron density and temperature are $n_e(0) = 2.6\times10^{19}$ m^{-3} and $T_e(0)$ = 1.9 keV respectively. The electron density is measured by two reflectometers (edge and core) with a 1 cm spatial resolution and a 10-chord interferometer. The electron temperature is measured by an ECE radiometer with 32 channels (2.5 cm spatial resolution). The above diagnostics have a time resolution between 1 and 4 ms. The impurity source term is given by peripheral line brightness along a horizontal diameter of the plasma as measured by a VUV spectrometer and the core impurity emission is measured by two soft-X ray cameras [4]. These impurity diagnostics have a time resolution of about 2 ms.

Injection techniques : The laser blow-off (LBO) injection system used in the present experiments is described in detail in [4]. Four metallic impurities have been injected with this system (TS38962-5): Al (Z = 13), Cr (Z = 24), Ni (Z = 28) and Ge (Z = 32). In order to extend the impurity charge range explored, we have performed supersonic pulsed injections [5] of small amounts (traces) of nitrogen (Z = 7) in a similar discharge (TS40783). While the common gas puff technique used in most previous studies produces a source term whose duration is of the same order as or higher than the particle confinement time (about 100 ms in

Tore Supra), the source term resulting from a supersonic injection is of a duration similar to that due to a laser blow-off injection (<10 ms). This new injection technique allows repeated injections in the same pulse. This allowed us to reduce the statistical uncertainties of the results without increasing the injected amount of atoms above the trace level.

Radial transport analysis : The flux is modelled as the sum of a diffusive term and a convective term :

$$\Gamma_Z = -D\nabla_r n_Z + V n_Z \qquad (1)$$

where D and V are assumed to be time independent. The 1D (radial) ITC code [4] uses prescribed transport coefficient radial profiles to resolve the system of time-dependent continuity equations for all the ionisation stages of the injected element :

$$\frac{\partial n_Z}{\partial t} + \vec{\nabla}\vec{\Gamma}_Z = S_{Z-1} + R_{Z+1} - (S_Z + R_Z) + s_Z \, .$$

(S_Z and R_Z denote the ionisation and recombination rates of the ionisation stage Z, and s_Z the external source). To optimise the transport determination, the way ITC is used depends on the experimental situation.

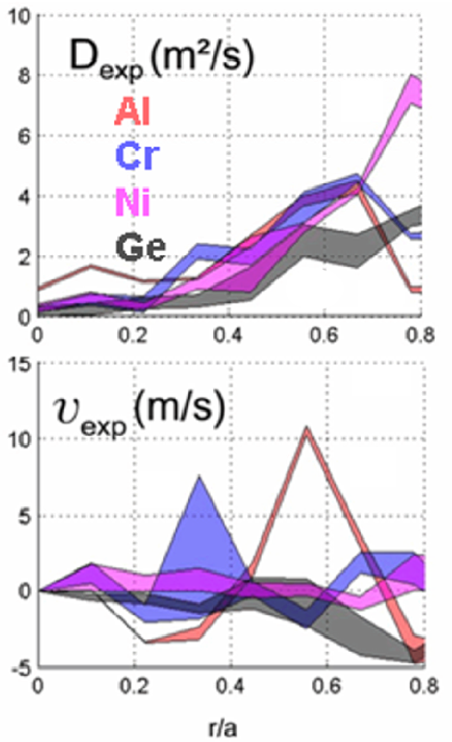

Figure 1 : D and V radial profiles for laser blow off injections of Al, Cr, Ni and Ge and (see text).

Laser blow-off injections : The procedure for the LBO injections is the following [4] : the ITC code starts from an initial guess of the D and V radial profiles. It solves the coupled continuity equations and reconstructs the emission measurements listed above. Then it modifies iteratively the transport coefficients until the difference between the reconstructed signals and the measured ones is minimised in a least squares (χ^2) sense [4]. The uncertainties (indicated in Figure 1 by coloured bands) have been obtained by varying the initial guess of the transport coefficient profiles and retaining all resulting solutions corresponding to the minimal χ^2 within a small tolerance. This first method aims at accounting for local minima. While the D profile seems essentially independent of Z, the various species exhibit very different V profiles with sign changes difficult to interpret. This is attributed to the fact that V appears in a derivative of lower order than D in the continuity equation.

Nitrogen injections: To compare the supersonic case with the gas puff case, we have used a slightly different procedure. The D and V values at each radial point are allowed to vary within an interval (red dashed lines in fig. 2) set by the user (the D profile is constrained to be monotonous). We have retained all the profiles corresponding to a $\chi^2 \leq 1.33\ \chi_{min}^2$ (Figure 2). This method indicates how more accurately D and V are determined in the supersonic case. As for LBO injections, the V determination is relatively uncertain. To improve the V determination we have combined the analysis of a supersonic injection with that of a stationary injection (which can provide only V/D). For the former (Fig. 3, lighter bands) we determine the best D and V profiles in the χ^2 sense (this time we do not put any constraint on the profile shape). The best D profile is used as a constraint in the stationary case while the V profile is adjusted to minimise the χ^2. A couple of iterations between the two cases ensure that a solution suitable for both is found (Fig. 3, darker bands). In both methods the error bands are obtained by varying the profiles around the solution and retaining those with a satisfactory χ^2. Note that the final V does not change sign along the minor radius. For this reason, and for the methodology reasons explained above, we consider the combined analysis as giving results more credible than the gas puff and the supersonic injection analysis alone.

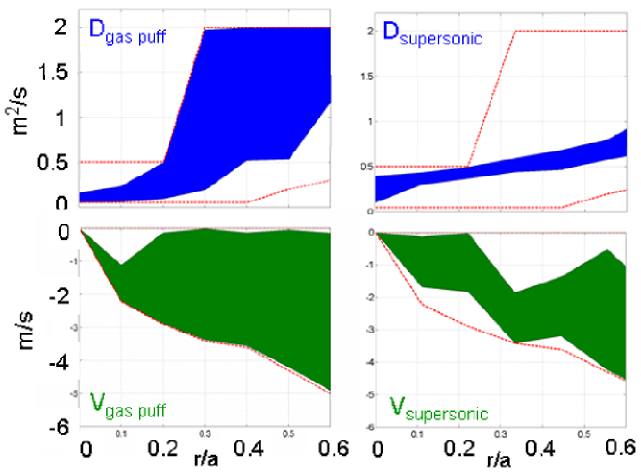

Figure 2 : Nitrogen (top) D and (bottom) V profiles for (left) a gas puff and (right) a supersonic nitrogen injection. (See text).

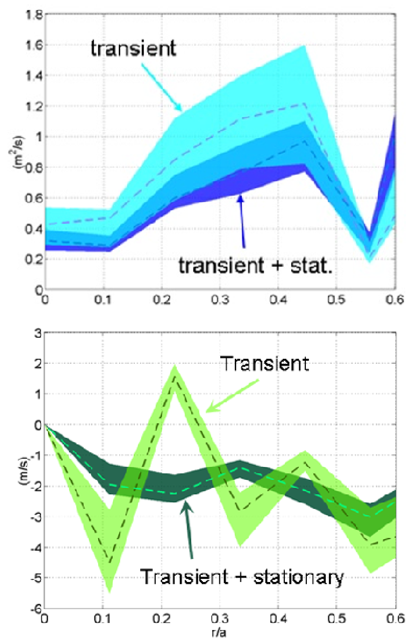

Figure 3: Nitrogen D (top) and V (bottom) profile. (see text).

Turbulent transport modelling : We use the quasi-linear gyrokinetic code QuaLiKiz [6] to determine the turbulent diffusion (Fig.5a) and convection velocity (Figs. 5b and 5c) profiles for the 5 injected species. Due to the n_e and T_e gradients, the turbulent diffusion is high even close to the plasma centre, in agreement with the experimental results (Figs. 1 and 3). Both terms of the convection velocity, namely the compression-curvature (CC, Fig. 5b) and thermodiffusion (TD, Fig. 5c) terms, are calculated. The TD velocity is outward (≥0) due to the fact that in our experiment ion temperature gradient modes are dominant. Its Z dependence is weak in the region where experimental results are available. Moreover, the CC term (which is Z-independent) is dominant, so that no V dependence on Z is expected in this scenario. The total turbulent V is inward, in agreement with the experimental result.

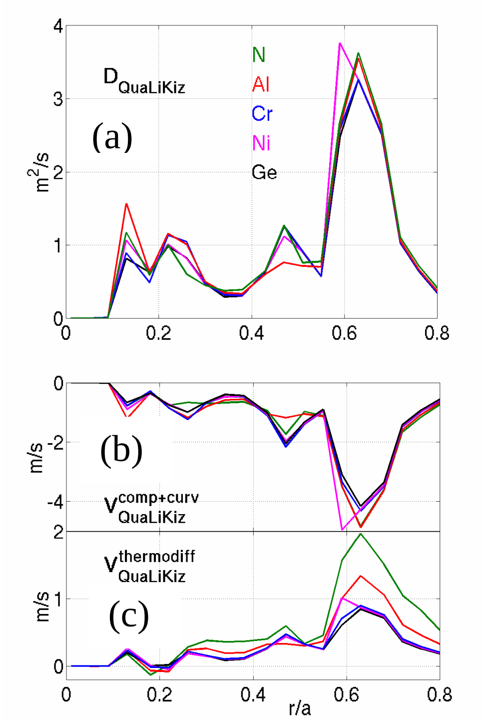

Figure 5: (a) Diffusion coefficient, (b) compression and curvature velocity, (c) thermodiffusion velocity from QuaLiKiz.

Conclusion : Impurity transport has been investigated over the Z range 7-32 in ohmic, sawtooth-free Tore Supra plasmas. 1) Supersonic pulsed injections allow a better determination of the transport coefficients than the usual gas puffing. V from a transient alone is less reliable than that from combination of a transient and a stationary injection (which can explain previous results on LH heated plasmas). 2) The experimental diffusion is anomalous everywhere and independent of Z, and the nitrogen convection is inward. 3) Gyrokinetic simulations predict that i) transport is governed by ITG turbulence even close to the plasma centre, ii) the turbulent V is inward, in agreement with the experiment, because the outward thermodiffusion term is weaker than the outward curvature term, iii) the Z dependence of V is weak in the Z range investigated.

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