*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.102 (2006)*

Charge and electron density dependences of anomalous impurity transport in Tore Supra

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Impurity transport in fusion plasmas is usually found to be (much) higher than neoclassical predictions. Moreover different results are obtained in different machines for similar scenarii (H mode, ITB, …). To explain these differences, turbulence is put forward. Theoretical models of turbulent impurity transport are now available, and parametric dependences will be a crucial test for their validation. This paper presents a study of the impurity charge (Z) and electron density (n_e) dependences of impurity transport measured in a series of Tore Supra ohmic, turbulence-dominated, discharges. First the experimental set up on Tore Supra is described, then the analysis method and its difficulties and limitations, and the experimental results. Finally these are compared with theoretical predictions, on the one hand with the neoclassical theory, and on the other hand with turbulence theory.

Experimental configuration

Experiments have been done in purely ohmic discharges where the main parameters were : R=2.4 m, a=0.72 m, B_T=3.4 T, I_p=1.2 MA, $n_e(0)$ = 2.7x10^{19} m^{-3} to 5.4x10^{19} m^{-3}, $T_e(0)$=1.6 to 2.8 keV. We made injections of several impurities : nitrogen (Z=7) by gas puff, aluminium (Z=13), titanium (Z=22), nickel (Z=28) and germanium (Z=32) by laser blow off. The laser injection is obtained by ablation of a thin metal layer (a few microns) deposited on a glass substrate. A 1J single pulse IR laser beam is focused on the target and creates a jet of metallic atoms towards the vacuum vessel, allowing injecting in each discharge one metallic impurity chosen among four targets. This injection system was recently reinstalled on Tore Supra and is found to be very efficient, reliable (>95% success rate) and reproducible. The electron temperature T_e is measured by an ECE radiometer and a Thomson scattering diagnostic. n_e is measured by two reflectometers with both excellent spatial (<1 cm) and time (2 ms) sampling period and a five-chord interferometer. Lastly, impurity emission is diagnosed by a V-UV spectrometer, bolometer arrays and a soft-X ray camera.

Analysis method

Non-perturbative impurity injections are used to determine independently the diffusion coefficient D and the drift velocity V in the radial impurity flux $\Gamma_Z = -D\nabla n_Z + Vn_Z$. An injection is non perturbative if it has no effect on T_e and n_e profiles, while spectroscopic data remain exploitable. In these conditions, the impurity contribution in measured signals is obtained by subtracting the background signals from the signals during the injection. The impurity density is generally not measured directly. It is extracted from integrated data of different diagnostics with an analysis code. On Tore Supra, we use a 1-D impurity transport code [1] improved with a new solver and a general magnetic configuration. Using a background plasma (n_e and T_e profiles, magnetic poloidal geometry), the code computes the radial evolution of all ionisation stages of a single impurity. It takes into account the atomic physics phenomena (ionisation/recombination) and D and V radial profiles provided by the user. Then spectroscopic data and geometry of the diagnostics are used to reconstruct simulated signals and to compare them with the measured ones. In order to reach the best agreement, D and V are modified step by step until simulation and experiment match at best.

The V-UV spectrometer provides very sharp data, as it discriminates between the different ionisation stages but the number of spectral lines observed is limited by the diagnostic capacity (2 or 3 lines at best) and its single line of sight (l.o.s.) configuration. For a better spatial resolution, we use bolometric arrays with 16 l.o.s. and soft-X rays cameras with 30 l.o.s. . Simulations prove that bolometric signals can be used with confidence for $r/a > 0.3$. Further in the centre, soft-X rays are the most efficient diagnostic as the emissivity is strongly central. The radial D profile is obtained from the inflow phase when impurity density gradients are very strong, implying an effect of D higher than V. Then in the decaying phase, V can also be solved simultaneously.

This analysis method contains some intrinsic limitations. First, the plasma edge description does not include potential toroidal and poloidal asymmetries. Secondly, the neutral jet ablated from the target has a time width of 400 μs [2]. The most peripheral signal measured (in general a spectral line emitted by a low-ionised stage) cannot be reproduced with such a source term. This peripheral spectral line has a much wider time evolution (a few 10 ms) and a different shape [3]. The solution retained here consists in taking this line time evolution as the neutral source. As a consequence, transport is undetermined for radii outside the emissivity region of the chosen ion but it also spares the issue of recycling.

Experimental results

Eight injections have been studied, allowing us to perform both Z (at intermediate density) and n_e scans, Z varying from 13 to 32 and n_e from $n_e(0) = 2.7\text{x}10^{19}$ m^{-3} to $5.4\text{x}10^{19}$ m^{-3}. Only a nickel injection has been deeply investigated, the others have been studied in a global confinement approach.

Previous studies on Tore Supra or JET did not find any Z dependence [4]. Temporal evolutions of soft-X ray data are compared for the different impurities : in a first

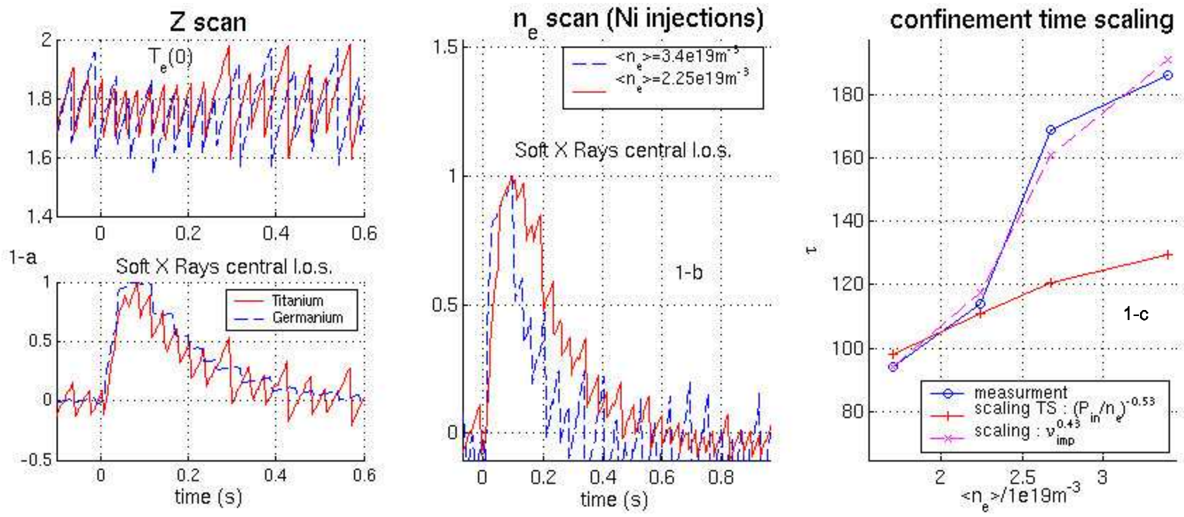
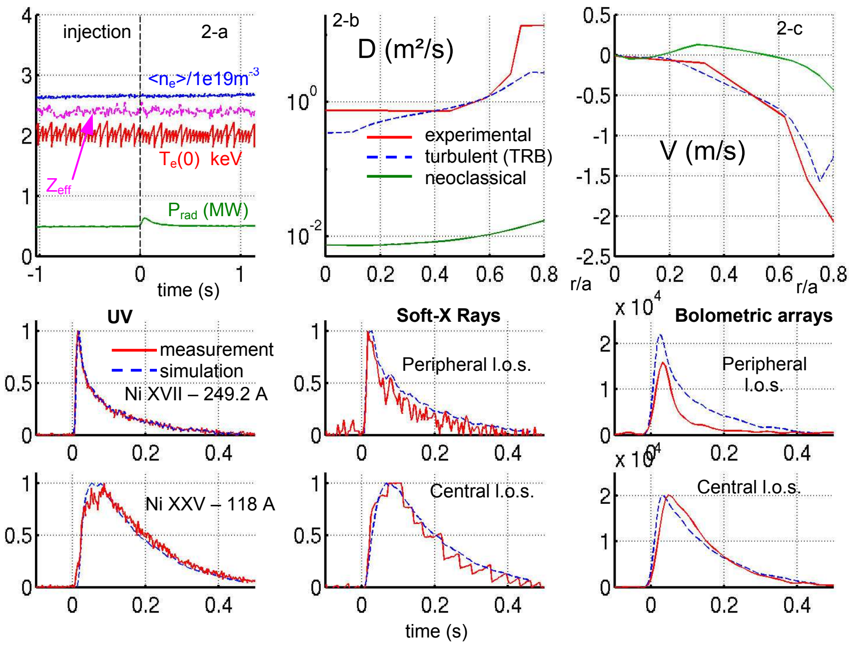


figure 1 : 0-D analysis of n_e and Z scans

approximation, the Full Width at Half Maximum τ of a central l.o.s. can be identified with the confinement time of the impurity. For the four metallic impurities, the result is hardly different. This is an argument for a turbulent diffusion since turbulent simulations made with TRB, a 3D gyro-fluid code [5], revealed the same lack of Z dependence for 13<Z<32. The strongest difference is more surprising (fig 1-a) : the influence of sawteeth is different for the different species, with a “stair” shape for germanium while titanium signal is more triangular. Sawteeth, visible on T_e, are identical, so that these differences can only been explained by transport and/or emission location reasons. However these differences need a complete study (in progress) to be explained. For nickel injections, the confinement time increases with n_e (fig 1-b). Moreover, the inflow phase duration also increases with n_e. As previously explained, these elements prove that the diffusion coefficient decreases when n_e increases. Global confinement time scaling is found to be different from [4] which could indicate an inappropriate parameter set in this previous scaling. We suggest another scaling, function of the central impurity collisionality ν^*_{imp} : in our experiments, τ scales as ${\nu^*_{imp}}^{0.43}$ (fig 1-c). However, the global β was not kept strictly constant and varied from 0.14% to 0.18% during these experiments.

An intermediate electron density with nickel injection discharge has been investigated in more detail (fig. 2). The neutral source is set after the emission of a Ni XVII spectral line (249.2 A), so that results outside r/a=0.8 are not presented. D and V profiles (2-b & 2-c) have been found to reproduce simultaneously at best a central stage ion line (Ni XXV – 118 Å), bolometric and soft-X ray data. They are sawteeth averaged as the specific phenomena happening around the q=1 surface are not taken into account. The neoclassical predictions obtained from analytical formulae [6] and the turbulent ones from TRB are also shown (2-b & 2-c). The un-calibrated turbulent predictions have been normalised to the measured ones at r/a=0.5 for a qualitative comparison. The experimental D is divided into three zones : an outer zone where the diffusion coefficient is the highest, a transition region and finally a central region where D reaches its lowest value. The diffusive part is clearly not neoclassical by nearly two orders of magnitude higher while, qualitatively, the turbulent D profile has a radial shape compatible with the experimental one. The experimental V is found to be negative (i.e. inward) and the normalised turbulent V profile has also a shape compatible with experiment. Neoclassical V does not match the experiment even if the difference is smaller than for D results.

figure 2 : analysis of a nickel injection



Conclusion

Different Z impurities have been injected in ohmic discharges in the Tore Supra tokamak. The confinement time does not depend on Z for 13<Z<32. An electron density scan with nickel injections shows that D decreases when n_e is increased and that the nickel confinement time scales as $\nu_{imp}^{*\ 0.43}$. A complete nickel injection analysis has been compared with theoretical predictions : the experimental D and V are qualitatively compatible with turbulent predictions and not with neoclassical values.

[1] M. Mattioli et al – Laser blow-off injection of metal impurities in Tore Supra – EUR-CEA-FC-1491 (1993)

[2] C. Breton et al – Low energy neutral beam production by laser vaporisation of metals – EUR-CEA-FC-1015 (1979)

[3] M. Mattioli et al, Nuclear Fusion 38 (1998) 189

[4] M. Mattioli et al, Nuclear Fusion 35 (1995) 1115

[5] N. Dubuit et al, submitted to Physics of Plasmas (2006)

[6] K. W. Wenzel and D. J. Sigmar, Nuclear Fusion 30 (1990) 1117