

# Z dependence of impurity transport in Tore Supra LH heated plasmas

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## Introduction

Impurity transport in a fusion plasma is an essential domain of investigation. On the one hand, impurity accumulation in the centre of the plasma causes fuel dilution and radiation power losses. On the other hand, impurities are intended to prevent too high heat fluxes onto ITER divertor plates by enhancing the radiation at the edge. For years, only the neoclassical theory has been available, but only few experiments exhibit such a behaviour. Experimental transport is usually orders of magnitude higher and is called «anomalous», attributed to turbulence triggered by electrostatic potential and/or magnetic field fluctuations. Recent theoretical developments [1] aim at making quantitative turbulent predictions and describing parametric dependences such as on the impurity charge  $Z$ . Recent experimental works [2] investigate this dependence. We report here a series of different species injections in LH heated sawtooth-free plasmas in Tore Supra (TS). First the experiments are briefly described. Then confinement time and transport coefficient analysis are presented. Finally, neoclassical and gyrokinetic quasi-linear analysis are made.

## Experimental results

Experiments are made in identical deuterium discharges with  $R_0=2.38$  m,  $a=0.72$  m,  $I_p=0.8$  MA,  $q_\psi=3.4$ ,  $B_T=3.7$  T,  $n_e(0)=5 \times 10^{19}$  m<sup>-3</sup> and  $T_e(0)=4.7$  keV. 2.8 MW of LH power are centrally deposited to suppress sawteeth. Impurities are injected by a laser ablation system and observed with a full set of diagnostics (described in [3]). Four species have been injected: aluminium ( $Z=13$  in red), chromium ( $Z=24$ , blue), nickel ( $Z=28$ , magenta) and germanium ( $Z=32$ , black). Even at the centre, impurities are not fully stripped, except for aluminium: the operational range of the  $Z$  scan in the central

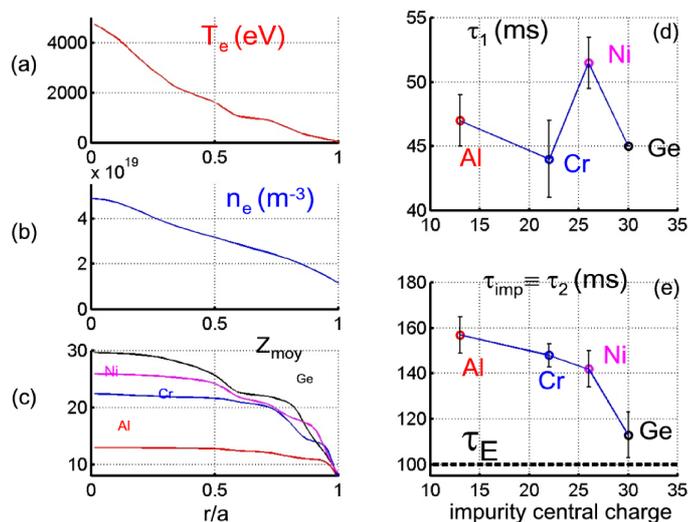


Figure 1: (a) and (b): electron temperature and density ; (c) impurity average charge (collisional-radiative model without transport) ; (d) and (e): short and long time constants of central soft X ray decrease.

region goes from 13 to 30. Injections are first analysed through an impurity confinement time study. To determine this time  $\tau_{\text{imp}}$ , we fit the exponential decrease of the central soft X-ray (strong central impurity emission) chord signal. Here, the attempt to measure  $\tau_{\text{imp}}$  reveals a first feature. Instead of a constant logarithmic slope during the decrease phase (usually found in ohmic discharges for example), we observe a clear break and the existence of two distinct time constants  $\tau_1$  and  $\tau_2$ . Thus we have to use two exponential functions ( $B(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}$ ,  $\tau_1 < \tau_2$ ) to match data well.  $\tau_1$  does not show a clear dependence on Z but  $\tau_2$ , assimilated with  $\tau_{\text{imp}}$ , decreases substantially with increasing Z, from 157 ms for aluminium to 113 ms for germanium. The existence of these two different time constants could indicate the presence of an inner region of the plasma where the transport would be very different (lower) from the outer plasma. The rapid time constant  $\tau_1$  would thus be representative for the transport in the outer plasma whereas  $\tau_2$  would give information on the inner plasma. This clear Z dependence of the impurity confinement time is different from what is expected from previous studies on JET and TS [4] where no Z dependence is reported in various conditions of TS plasmas, from ohmic to L-mode plasmas. In addition, our own experiments in ohmic plasmas with or without sawteeth (not shown in this paper) show the same lack of Z dependence.

### Transport analysis

The four injections have been analysed with the impurity transport code ITC [3] to extract the transport coefficients (Fig. 2 (a1-a2)). For each impurity, the D and v profiles which best reproduce measurement time evolutions are plotted. This is performed using a gradient search  $\chi^2$  minimization method: the retained values for D and v allow a 15 % variation of  $\chi^2$  from its minimal value. A comparison between measurements and simulations (b1-b4) is presented with the central

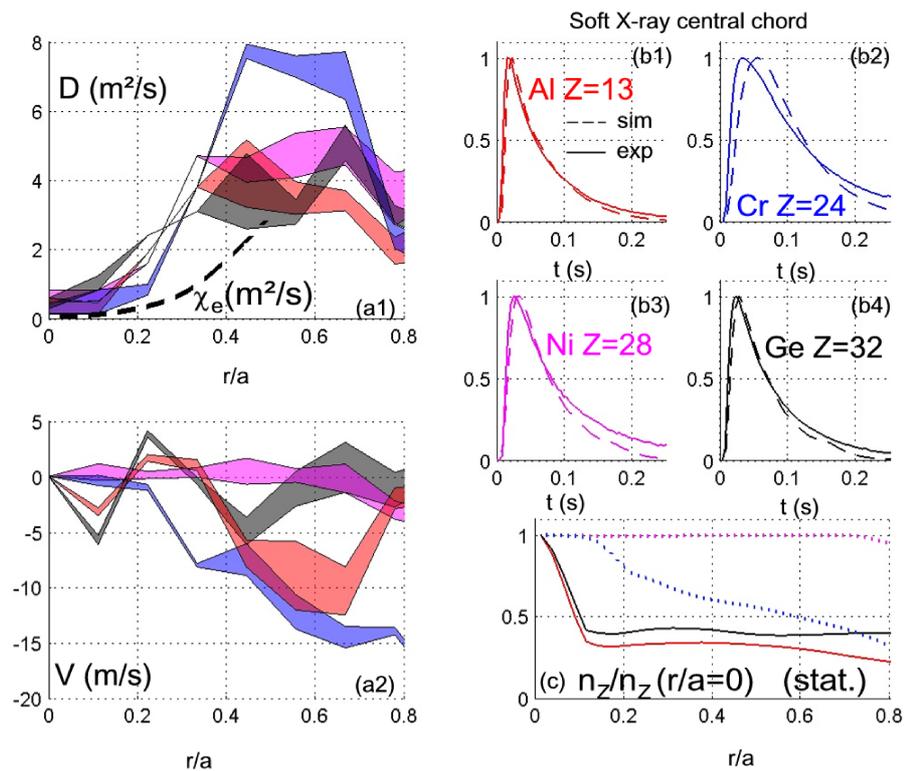


Figure 2: Transport coefficients. (a1) Impurity and electron heat diffusion. (a2) Impurity convection. (b1-b4) Simulation vs measurement. (c) Stationary impurity density

presented with the central soft X-ray chord to illustrate the quality of the simulation. The results for chromium should be taken

with some care as the source term is poorly diagnosed. The other three simulations are much better, especially for aluminium and germanium. The D profile is very similar for the four impurities. As expected, we find an outer region from  $r/a=0.35$  to the edge where the diffusion coefficient is strong, between 3 and 5  $\text{m}^2\cdot\text{s}^{-1}$ . Then a transition zone to the very central region ( $r/a<0.2$ ) where the diffusion coefficient falls to a value between 0.4 and 0.7  $\text{m}^2\cdot\text{s}^{-1}$ . In the central zone, no Z dependence appears taking into account the error bars. The analysis of convection velocity is ambiguous. For the aluminium and germanium cases, the quality of the simulations is good enough to take the result with confidence. They are quite similar in shape between  $r/a=0$  and  $r/a<0.45$  with a change of sign near  $r/a=0.2$ . The sensitivity on  $v$  for nickel is weak and causes its value to be alternatively positive and negative,  $v\approx 0$ . The best simulations (aluminium and germanium) both show very peaked stationary density profiles (c) consistent with what was expected from confinement times and radial shapes of the soft X-ray brightnesses (very peaked at the very centre of the plasma ( $r/a<0.1$ )).

### Neoclassical and turbulence analysis

Neoclassical predictions (Fig. 3 (a): analytical formulae [5]) seem not compatible with these measurements as D and  $v$  are too low by at least one order of magnitude. Thus we use QuaLiKiz [1] (gyrokinetic quasi-linear with fixed gradients) and TRB [6] (non linear gyrofluid with fixed sources) simulations to evidence possible Z and A (the mass number) dependences of impurity transport and check approximated analytical dependences. The  $n_e$

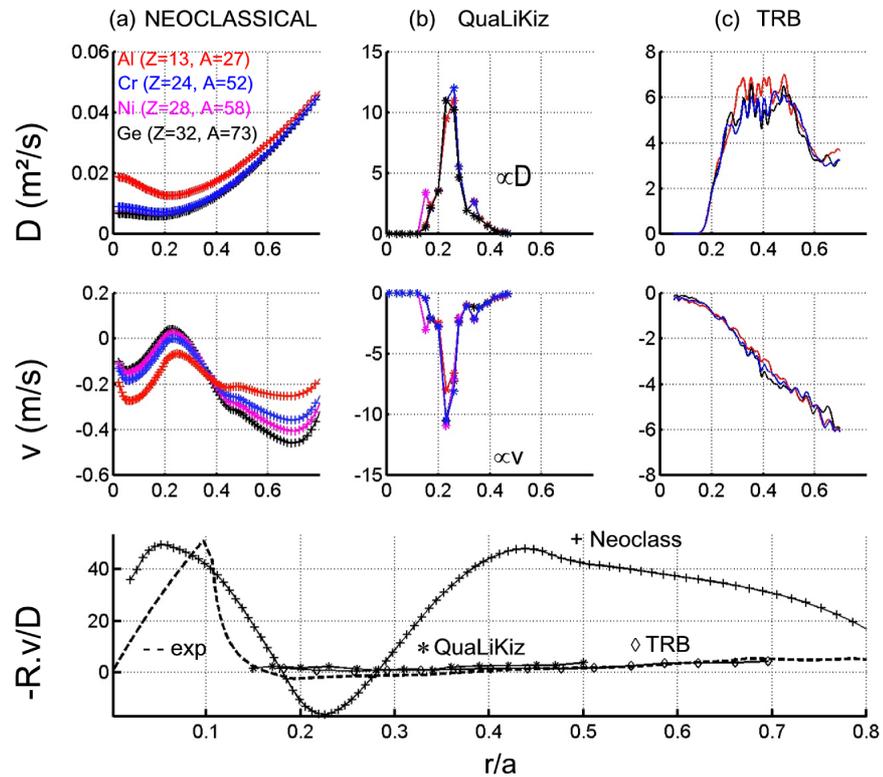


Figure 3: (a) Neoclassical. (b) QuaLiKiz. (c) TRB. (d) Germanium peaking parameter for experiment and theoretical predictions

and  $T_e$  measurement accuracy is sufficient to study gradients for  $0<r/a<0.5$ . The gyrokinetic linear code Kinezero is thus used here to study the nature of the turbulence: the modes are found to rotate in the ion drift direction. The collisionality has been varied to test trapped electron effects ( $\nu^* \times 0.02$  to 50): they contribute substantially to the turbulence that is a mix of Ion Temperature Gradient modes and Trapped Electron Modes. Then, the results are used in a new quasi-linear cal-

ulation QuaLiKiz, giving the impurity radial flux. Independently, TRB simulations with varied species are performed. The turbulent  $D$  and  $v$  ( $v$  is governed by compressibility term of passing impurities) reveal to be weakly or not dependent on  $Z$  and  $A$ . For the diffusion coefficient  $D$ , a transition between a central zone with no turbulence and the outer turbulent plasma is predicted consistently by both codes ( $r/a \approx 0.15$ ). The  $D_{\text{TRB}}$  profile is very close to the experimental one, while QuaLiKiz is unable to reproduce the anomalous outer region, possibly due to uncertainties in the measured gradients.. Concerning the turbulent convection velocity, it is found to be inward everywhere in both cases. Finally, the peaking parameter is plotted (c) and reveals a strong similarity between experimental and neoclassical central transport for  $r/a < 0.2$ . We have to stress here that taking for germanium these neoclassical values for an ITC simulation lead to quite good simulations, even if not as good as those presented before. This raises the question of the sensitivity of ITC simulations to  $D$  and  $v$  in the centre of the plasma for these weak values. But it is also an encouraging step for the aim of being able in the near future to make quantitative predictive computations for impurity transport.

### Summary

Four impurities (Al, Cr, Ni, Ge) have been injected into LH heated sawtooth-free Tore Supra plasmas. The 1D transport analysis shows the existence of a central zone ( $r/a < 0.2$ ) where diffusion is strongly reduced and convection strongly inward, leading to very peaked impurity density profiles. In the central zone, the neoclassical peaking factor  $v_{\text{NC}}/D_{\text{NC}}$  is compatible with the experimental one for Ge but the  $Z$  dependence of the peaking factor is not the observed one. Moreover, the soft X-ray brightness analysis indicates a decrease of the impurity confinement time (from 157 ms for Al to 113 ms for Ge) with increasing  $Z$ , contrary to the neoclassical prediction. The frontier location between the two zones, the turbulence quench in the central zone and the peaking factor in the outer zone are correctly predicted by two turbulent transport codes: the fixed gradient, linear gyrokinetic code QuaLiKiz and the fixed flux, nonlinear gyrofluid code TRB. Neither code predicts a  $Z$  dependence of the transport coefficients. The diffusion coefficient profile deduced from TRB is consistent with the experimental one while QuaLiKiz fails to reproduce the observation for  $r/a > 0.4$ , probably due to the suprathreshold electron pollution of the  $T_e$  gradient in the outer plasma. More experiments will be analysed in the near future to study the role of the heating scheme on the driving transport mechanism and the transport coefficient dependence on the impurity charge.

### References

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