Comparison of Measured Impurity Transport Parameters with Theoretical Predictions

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COMPARISON OF MEASURED IMPURITY TRANSPORT PARAMETERS WITH THEORETICAL PREDICTIONS

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1. Introduction

Systematic studies conducted on JET with the laser blow-off injection technique have demonstrated that in most cases the transport of trace impurities is much slower in the plasma centre than in the rest of the discharge. Very accurate simulations of the space resolved broad band soft X-ray emissivities and of line intensities from the highly ionised states of the injected impurity can be obtained assuming the impurity diffusion coefficient D to have constant values, D_{in} and D_{out} respectively, in a certain core region and over most of the remaining plasma cross section, the transition between the two levels occurring over a narrow intermediate radial region[1]. Similar conclusions have also been obtained for the particle transport of electrons and intrinsic impurities. The values of D and the size of the inner region of slow transport are seen to vary with the main parameters of the discharge. In this paper we summarise our experimental evidence for L-mode and compare it with theoretical predictions.

2. Experimental Evidence

Although the D profile described above is schematic, it is clear from the transport analysis that its value has to undergo a very strong reduction (typically more than an order of magnitude) within a radial distance that in most cases cannot be larger than 25 cm. The levels D_{in} and D_{out} have to be considered average values over the slow and fast transport region respectively. A practical measure of the size of the former region can be deduced from the distance d(t), along the major radius on the tokamak's equatorial plane π, of the two maxima (on either side of the magnetic axis) in the perturbation of the soft X-ray emissivity induced by the injected impurities during their ingress into the plasma. After an initial rapid decrease during the first

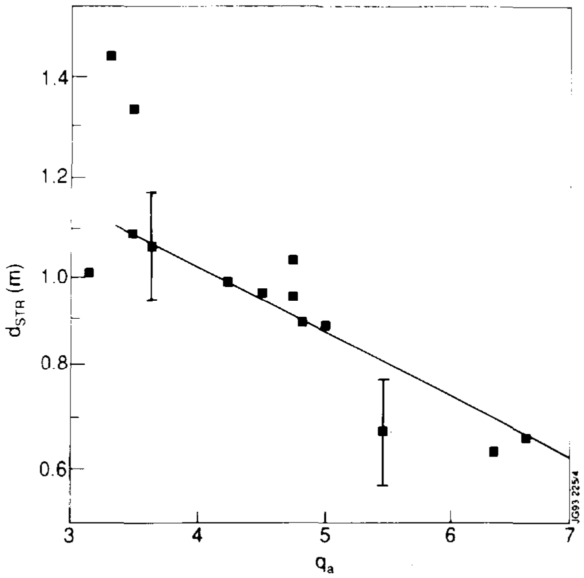

Fig. 1 Horizontal diameter of the slow transport region versus the edge value of the safety factor for L-mode limiter discharges.

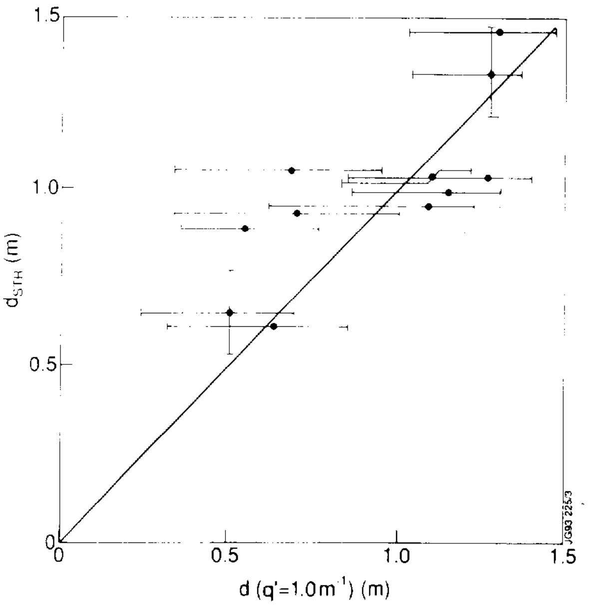

Fig. 2 Horizontal diameter of the slow transport region versus the hor. diam. of the flux surface where q' = 1.0 m^{-1} for L-mode limiter discharges.

20 - 30 ms following the injection at $t = t_0$, the time variation of d(t) practically comes to a halt indicating a strong slowing-down of the impurities inward propagation. We take the value $d_{STR} = d(t_0 + 30\ \text{ms})$ as the horizontal diameter of that slow transport region. In fig. 1 this quantity is plotted versus the edge value q_a of the safety factor for pulses with current and magnetic field in the ranges I_p = 2 - 7 MA and B_T = 1.45 - 3.4 T.

The empirical dependence of d_{STR} on the global parameter q_a appears to be due to a strong correlation between high levels of D and high magnetic shear. The same quantity is plotted in fig. 2 versus the horizontal diameter of the flux surface S where $q' \equiv \partial q/\partial R_{ext} = 1.0\ \text{m}^{-1}$. Here R_{ext} is the outer major radius of S in the plane π. The good correlation of the two quantities indicates that the radial extent of the region of slow transport increases when the q profile is flat over a wider area. Most of the points in the plot refer to quasi-steady (sawteeth-affected) current profiles, but a few of them were obtained from experiments performed during the current rise or decay.

The average level D_{in} of the impurity diffusion coefficient in the region of slow transport, known with an uncertainty of ± 70%, ranges between 0.03 and 0.15 m^2/s. No parametric dependence has been identified; probably because of the large experimental uncertainty.

The level of D_{out} appears to be well ordered by the empirical operational parameter $P/\langle n_e \rangle$, the ratio of the total heating power to the average electron density. Indeed for fixed I_p and B_T (i.e. for similar q profiles) the same parameter appears to order the

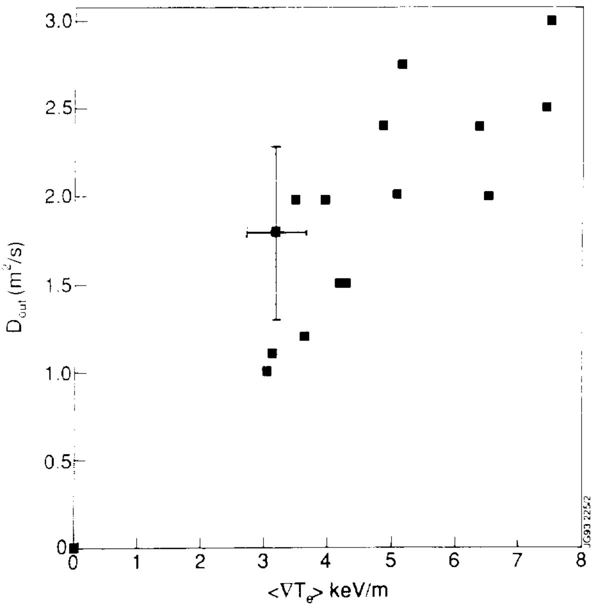

Fig. 3 Average level of the impurity diffusion coefficient in the external fast transport region versus the average over the same region of the electron temperature gradient for L-mode limiter discharges.

measured decay times τ_I for the whole data set of JET experiments of non recycling impurity injection. For the pulses where spatial transport analysis has been performed, this quantity is also in good correlation with the average value of the electron temperature gradient $\langle\nabla T_e\rangle$ over the region where the transport is fast. The relationship between the levels of D_{out} and $\langle\nabla T_e\rangle$ is shown in fig. 3. The data are consistent with a power law dependence $D_{out} \propto \langle\nabla T_e\rangle^{0.85 \pm 0.2}$. The dependence on $\langle\nabla T_e\rangle$ cannot be distinguished from a dependence on T_e (or from a dependence on T_i or its gradient) because of the strong collinearity between these two parameters (and because of lack of information on the T_i profile as most of the analysed pulses were run without neutral beam additional heating). From the comparison of pulses with practically identical temperature profiles it appears that the level of the electron density (or of its gradient) has no appreciable influence on D_{out} [2].

3. Comparison with Theories

The comparison of measured diffusivities D_{in} in the centre with the neoclassical predictions shows that, for intermediate ion charge ($Z \approx 25$ to 40) impurities (for which neoclassical diffusivities D_{neo} as low as 0.01 m^2/sec can be expected in some cases) and for moderate to high values of the central temperature, D_{in} is systematically higher, by a factor of 2 to 10, than D_{neo}. Furthermore, while a strong influence of the ion temperature and of the magnetic field on D_{neo} is predicted by the theory, no such dependencies can be inferred from the experiments. Therefore we have to conclude that the neoclassical theory does not fully account for the diffusion in the central region.

The theoretical evaluations of anomalous diffusion from analyses of unstable internal modes are generally based on the mixing length argument, as well as on a number of simplifying assumptions (e.g. on plasma geometry), and therefore are only expected to supply rough approximations. Their parametric dependence should however be consistent with the observed experimental trends. In particular an adequate theoretical model of our test particle transport experiments should predict the very low anomaly in the diffusion at the plasma centre (that was found not to be dependent on the details of the density and temperature profiles) as well as its established dependence on the rotational transform profile.

A recent extension of the Rebut-Lallia-Watkins[3] semi-empirical model to include particle transport assumes simple proportionality between D and χ. This model gives naturally, for most cases, a central feature for D *similar* to the one found in the experiments, although not in close quantitative agreement. This is due to relatively low ∇T_e (lower than ∇T_{crit}) in the central region when sawtooth activity flattens the T_e profile within the mixing radius (see fig. 4). However difficulties arise when ∇T_e is large in the centre (e.g. monster-sawteeth).

Microturbulence models based on ion temperature gradient (ITG) driven modes generally predict too high values for the plasma centre, although some authors observe that more detailed analysis of the mode radial structure leads to substantial modifications of the radial dependence of the diffusion coefficients. In particular the quasi-linear estimate from Romanelli[4] in the limit of small shear ($s \equiv rq'/q < 1$) for the correlation length of the turbulence $L_r \approx 3\, L_l \exp[-c\, q^{-4/3} s^{-1}]$, where $L_l = |\mathrm{dln}f/dr|$, $f = (r^2/a^3)(1/q^2)\, T_{e0} T_{i0} (T_e dT_i/dr)^{-1}$ and c is O(1), implies a very strong radial variability of the diffusion coefficient, that we may roughly estimate as $D_R \approx L_r^2\, v_{ti}/R$. At the radial position r_c where L_r becomes $O(\rho_i/s)$ the value of D_R is comparable to those previously reported on the basis of 1-dimensional analyses and is of the order of a few m²/s. Here R is the tokamak's major radius, ρ_i the gyroradius of the main ions and v_{ti} their thermal speed. For $r < r_c$, an exponential quenching is predicted for D_R and the effect of turbulence is expected to be reduced drastically. Adopting therefore $L_r = \rho_i/s$ as a threshold condition for the transition from slow to fast anomalous transport we obtain $sq^{4/3} \approx c/\ln(3sL_l/\rho_i)$. A condition of this kind is not very different from the empirical condition found on JET ($q' \approx 1\ \mathrm{m}^{-1}$).

A different approach is suggested by Beklemishev and Horton[5]. They argue that the radial variation of the density of resonant states ($q=m/n$), that is strictly linked to the shear, strongly influence the shape of the diffusivity profiles. Inclusion of this effect leads to *model D profiles* more closely linked in shape to the experimental ones, with consistently low diffusivity in the inner core of the discharge (fig 4).

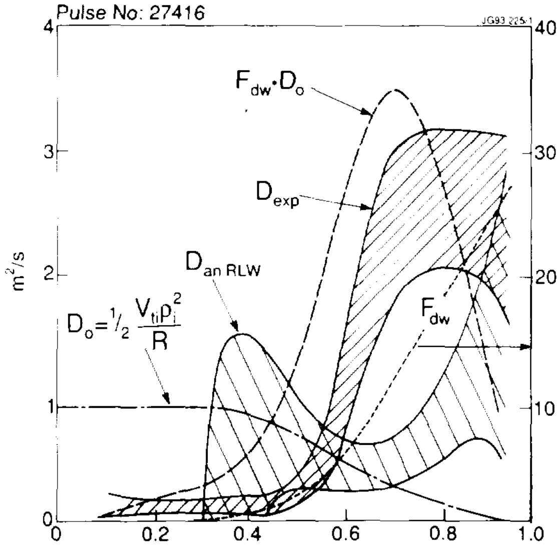

Fig. 4 • Experimental profile of the diffusion coefficient D_{exp} for injected Ni in a 5 MA, 3.2 T, P_{RF}=4 MW, ⁴He discharge.

• Profile of the anomalous particle diff. coeff. D_{anRLW} according to ref. 3.

• Profile of the typical scale D_0 of ITG turbulence induced diffusivity, as usually deduced from local analysis; correction coefficient F_{dw} according to ref. 5 to account for the uneven distribution of resonant magnetic surfaces; *corrected* model diffusion coefficient $F_{dw}\, D_0$.

4. Conclusions

Diffusion of impurities is moderately anomalous in the core of the plasma and much larger further out. The size of the region where the transport is slow increases when the q profile is flat over a wider area. Transport modelling based on the critical ∇T_e assumption leads to *similar* shapes of D profiles when the temperature profiles are flat in the centre. Early attempts to describe the radial structure of microturbulence suggest that the anomalous diffusion due to ITG driven modes should be much smaller when the magnetic shear is low.

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