A Semi-empirical Drift-wave Model for the Simulation of Impurity Transport and Comparison with JET Experiments.

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Results from systematic studies on trace impurities (Ni, Fe, Mo) injected into L-mode plasmas in JET have characterised the radial and parametric dependences of the impurity diffusivity D and convective velocity v, where the flux Γ_Z is $\Gamma_Z=-D\nabla n_Z+vn_Z$ [1,2]: the transport, dominated by diffusion over most of the bulk plasma, is slow (but still 2-10 times neoclassical) inside a critical radius r_c, while in the outer region is highly anomalous and scales in a similar manner to heat transport with average outer values of $D \propto \nabla T_e$. The radius r_c can be identified with the position where the magnetic shear $s \equiv \frac{d(\ln q)}{d(\ln r)} \cong 0.5$ (with q being the safety factor and r the radial coordinate along the minor radius, a).

The theoretical transport coefficients (in particular their radial dependence) derived from various electro-static microinstabilities will be assessed against their experimental measurements, with particular attention to the performance of the models in sawtoothing and sawtooth-free plasmas with various currents and q-profiles. The L-mode pulses analysed are:

#	inj.imp.	I (MA)	$n_e(0)$ 10^{19} m^{-3}	$T_e(0)$ keV	$x_c=r_c/a$
27414	Ni	2	3.8	4	0.35
27410	Ni	3	4.7	4.5	0.38
27416	Ni	5	3.3	4.8	0.56
18112	Mo	3	2.9	9	0.38
27342	Fe	3.5	4.7	4.2	0.43

In all these cases the electron density profiles are fairly flat in the central region. The discharge 18112 is a monster sawtooth (note the high central T_e); all other discharges have flattened T_e profiles in the central region, due to the sawtooth activity. Also it has been assumed $T_i = T_e$ as no measurements of the T_i profiles were available.

Only trace levels of impurity were injected, and are therefore not expected themselves to excite impurity driven modes. For such low impurity concentrations the transport is determined by pure plasma modes and will be assessed in slab and in toroidal geometry.

SLAB MODES.

1. Ion temperature gradient (ITG) from Horton et al.[3]: the analysis in slab geometry is relevant only when $L_s<R/2$, where $L_s=Rq/s$ is the shear length and R the major radius. This inequality is not satisfied for the above shots. This was observed also in the shots used to analyse the ion thermal transport [4] and appears to be a general characteristic of JET discharges, so that the slab ITG mode cannot be invoked to interpret transport in JET.

2.Trapped Electron-driven Mode from Gang et al.[5]: the analysis is applicable only when $s\sqrt{L_s / L_n}\, k_\vartheta \rho_s \rangle 1$, with k_ϑ the poloidal mode number, ρ_s the ion Larmor radius evaluated with the electron temperature and $L_n = n / \nabla n$ the electron density profile scale length. Regions of marginal validity for this model may exist towards the plasma edge. But, the predicted diffusivity contains a $T_e^{3/2}$ term (pure gyro-Bohm scaling) which leads to a radially decreasing profile, in contrast with the experimental observations.

TOROIDAL MODES

1. Toroidal ITG mode from Romanelli [6].

The expression of D for this instability is predicted to be:

$D \approx \frac{\varepsilon_n}{\sqrt{\tau}}\sqrt{\frac{\eta_i^{0.5}}{s q \varepsilon_n^{0.5}}}\, \frac{\rho_i^2 v_{th,i}}{L_n}$, where $\eta_i = \frac{L_n}{L_T}$ with the temperature scale length $L_T = \frac{T}{\nabla T}$, $\varepsilon_n = \frac{L_n}{R}$, $\tau = \frac{T_e}{T_i}$, ρ_i the ion Larmor radius and $v_{th,i}$ the ion thermal speed. This result is valid when $\eta_i \rangle \eta_c$ with η_c given in [6]. Fig.1 shows the radial shape of the diffusivity predicted from this model for the chosen discharges. A pure gyro-Bohm scaling $(\rho_i^2 v_{th,i} / L_n)$ is also implied and causes difficulties in the outer region. The monster sawtooth (pulse 18112), for which $\eta_i \rangle \eta_c$ even in the central region, clearly shows that this model's prediction cannot be reconciled with the experimental results shown in fig.3.

2. Trapped Ion Instability (ITG driven) from Biglari et al.[7].

The quasi-linear estimate of the impurity diffusion coefficient is :

$D \approx \frac{k_\vartheta \rho_i}{4}\sqrt{\frac{\varepsilon_n \sqrt{2\varepsilon}}{1+\tau}}\left(1+\eta_i\right)^{1.5} \frac{\rho_i^2 v_{th,i}}{L_n}$ and is shown in fig.2. The central depression predicted by this theory in sawtoothing discharges is a consequence of the flattening of the temperature profile, as is clearly demonstrated by the poor prediction in the case of the peaked temperature profile (pulse 18112).

In conclusion, conventional models based on drift-wave mechanisms are unsatisfactory for the main reason that the diffusivity associated with these waves assumes the radial correlation length $L_r = O(\rho_i)$. Therefore, due to the resulting dominant $T^{3/2}$ (gyro-Bohm) dependence (which it is difficult to offset by other geometrical factors) the diffusivity (in the absence of stability threshold effects) decreases towards the outer region.

TOROIDAL COUPLING of MODES

Global mode structures due to toroidal coupling [8,9] of neighbouring modes can be invoked to provide an enhanced estimate of the correlation length $L_r \approx (a\rho_i/s)^{1/2} \exp(-c/s)$, with c being a constant O(1). This has led to a semi-empirical model, whose explicit expressions for the transport coefficients are:

$D = \alpha D_B \left| \frac{a}{L_T} \right| \frac{\exp(\frac{-2c}{s})}{s}$ and $v = -\frac{D}{R}$, where D_B is the usual Bohm value.

This form fits the required decrease in the low-shear region (irrespective of the sawtooth activity) and dependence on the temperature gradient. It is also independent of the impurity charge Z and is close to the Bohm-like coefficient for energy transport proposed in ref.[10]. The shape function $\exp(\frac{-2c}{s})/s$ vanishes towards the plasma centre where s→0. In this region, however, L_r should not fall below ρ_i; therefore a gyro-Bohm-like term needs to be added in order to have a residual transport in the region of low shear. The resulting diffusivity is then: $D = \alpha D_B \{ |a/L_T| \exp(\frac{-2c}{s})/s + \beta \frac{\rho_i}{a} \}$

The set of values for the numerical factors α, β and c in this semi-empirical model that give a reasonable prediction for both the radial extent of the low transport region and the average magnitude of the diffusivity in the region of fast transport for all the discharges is: α=0.008-0.01, β=3.5-4.0, c=1.2-1.4. The resulting semi-empirical diffusivities are shown in fig.3 and they are compared with the corresponding experimental ones [1].

This model is not expected to describe the last few cm close to the separatrix. An ad hoc treatment of this region is needed [11] for the predictive simulation, i.e. a peripheral transport barrier (decrease of D and strong increase of the inward pinch v) preventing too fast an outward diffusion of the lower to intermediate ionised states.

Diffusion is the dominant transport mechanism, but a small convection is still necessary for a good simulation of the time evolution of the brightness lines [1]. The v predicted by this model is probably too small, and does not vanish in the centre, as would be desirable.

As an example of the performance of the model, fig.4 shows the experimental profiles of the perturbation $\Delta\varepsilon_{SXR}$ to the soft X-ray emissivity and their simulation for pulse #27410.

CONCLUSIONS

The conventional drift-wave models fail since they have a pure gyro-Bohm scaling.

The enhancement of the correlation length due to the toroidal coupling of neighbouring modes has led to a promising expression for the anomalous transport coefficients.

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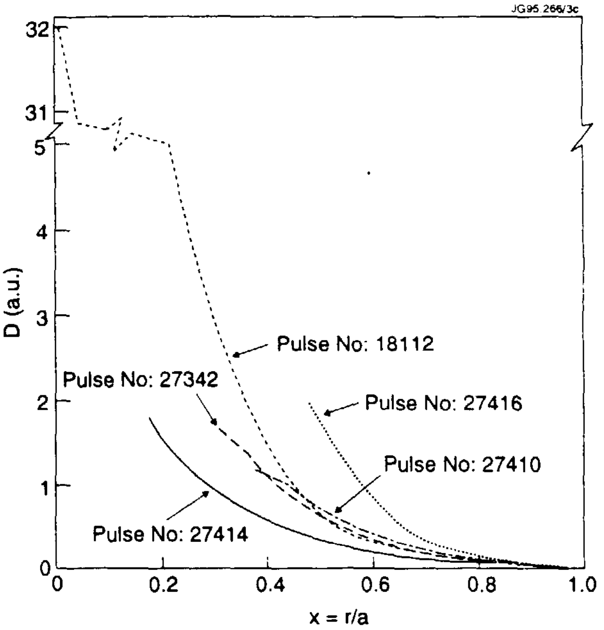

Fig.1.Predictions of the quasi-linear estimate of D based on the toroidal ITG mode.

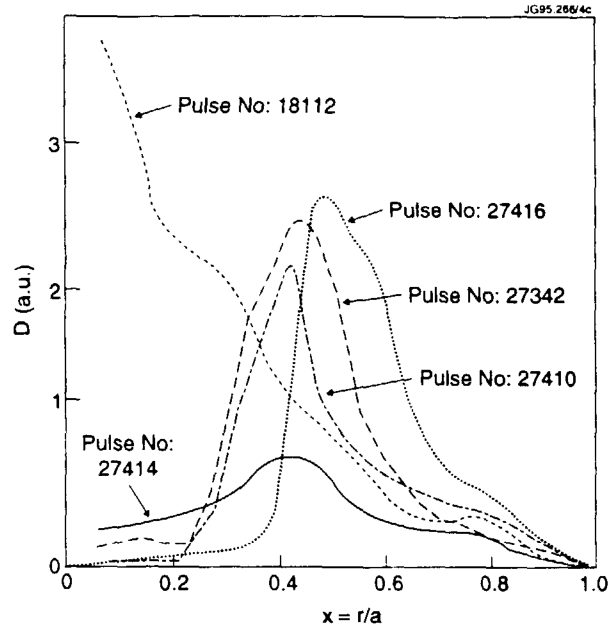

Fig.2.Predictions for the quasi-linear estimate of D based on the trapped-ion mode.

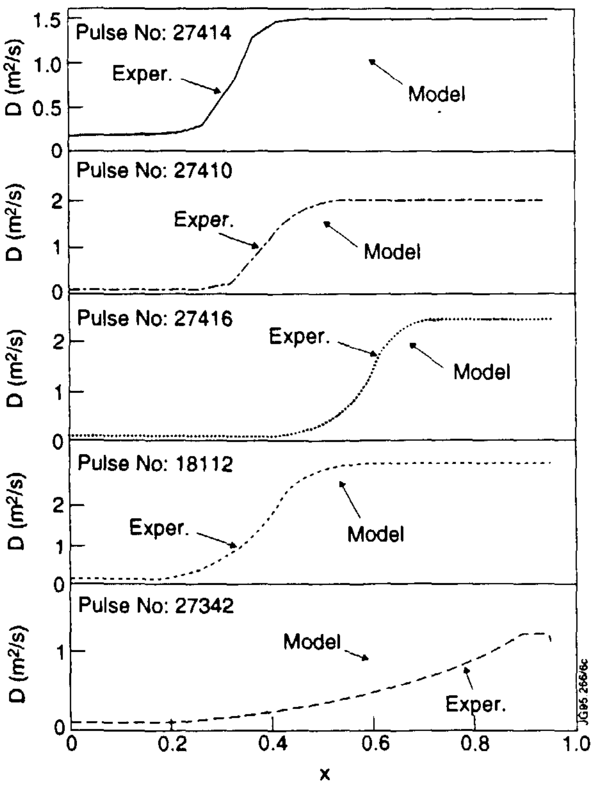

Fig.3.Comparison of the experimental D with the one predicted from the semi-empirical model for each pulse.

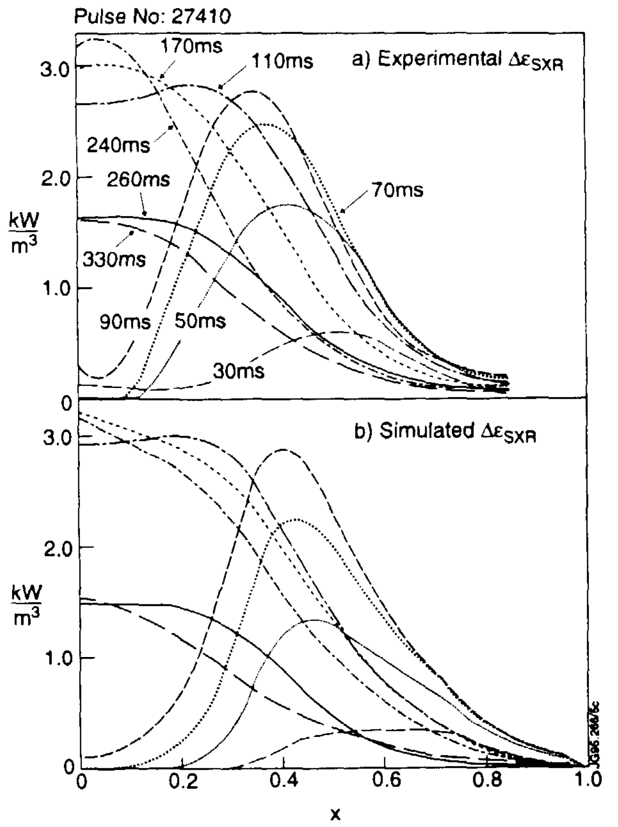

Fig.4.Experimental and simulated emissivity profiles for discharge #27410.