Multifluid Modelling of Radiative and Detached Edge Plasmas and Comparison with JET Experimental Results.

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Introduction

The multifluid code EDGE2D/U, coupled to the neutral Monte Carlo code NIMBUS, and its newly developed post-processor provide a means to simulate and compare with experimental results the distribution of the deuterium and impurity density, temperature and flow, and related quantities such as ion saturation current density J_s at Langmuir probes, D_α and bremsstrahlung radiation signals, and the impurity and deuterium radiation power density.

By this means we studied the route to plasma detachment in the JET Mark I divertor and the related role of impurities and impurity radiation for ohmic and L-mode discharges, mainly for cases where carbon was the main impurity species.

In EDGE2D/U transport is collisional in the parallel direction and anomalous across flux surfaces. The anomalous particle transport model, assumed to be the same for deuterium and carbon, includes as an option a non diffusive 'inward pinch' term: $\Gamma=-D\nabla n-nV$. Typically:

$D=1m^2/s$, $\chi_e = \chi_i = 1.5m^2/s$, $V=15m/s$, (pinch model),

$D=0.1m^2/s$, $\chi_e = \chi_i = 1.5\ m^2/s$, $V=0$ (no pinch model).

In most simulations these coefficients were chosen constant in space. In the few cases without a pinch shown here they were constant in flux space, which essentially implies a linear dependence on the local safety factor q in real space.

The power P entering the SOL (assuming $P_e=P_i$) and the mid-plane separatrix density n_s were prescribed consistently with experimental observations. Uniform carbon puffing from divertor targets replaces sputtering, because sputtering models available in the code are not sufficiently accurate (e.g. physical sputtering fails completely to reproduce observations). The carbon content was automatically adjusted via puffing to reach and maintain a level of radiation consistent with experimental data.

Route to detachment

Experimental results in JET and other Tokamaks show that as plasma density and radiation losses increase in a discharge, the flow of particles to the divertor targets first increases then rolls over and finally decreases to very low levels (plasma detachment). In the detached phase flows of momentum ($\Rightarrow$ pressure) and energy to the targets are also reduced. Detachment is usually stronger at the inner target and requires impurity radiation even for ohmic discharges.

Another experimental observation is the increase with time of D_α signals going from the low recycling to the high recycling phase and finally to the detached phase of a discharge.

All of these trends are reproduced by our simulations. As an example fig. 1 compares experimental and computed peak values of J_s for an ohmic discharge (#31627) at times corresponding to low recycling, high recycling and detachment at the inner and outer target (model with pinch). Fig. 2 shows a similar comparison of D_α signals integrated along lines of sight across the inner and outer divertor zones for the same discharge.

The radiated power required in the divertor zone for detachment in our simulations is somewhat higher (20-30%) than in experiments. This may reflect uncertainties both in measurements and modelling. For example, it might indicate that some carbon (or other impurity) is generated outside the divertor and not only at the targets or that the assumed value n_s=1.25 10^{19} is too low. The best values of J_s in fig.1 at t≈16.7s were obtained by puffing carbon from the outside divertor wall, in addition to that from the targets.

A typical problem with purely diffusive models is that with increasing density the ionization source inside the separatrix and the parallel flow become too small to provide the expected SOL density decay, even with very small values of D. The effect is stronger at high input power. In addition a purely diffusive model does not simulate the increase in J_s observed in the attached high recycling phase of a discharge. An ad hoc influx of particles from the plasma core, e.g. compensating some pumping, provides proper density profiles. However, unless a realistic path for neutrals to cross the separatrix is found, (see discussion in [1]) it is likely that these results indicate that purely diffusive perpendicular transport models are incomplete.

We introduced a pinch term in the SOL and the divertor regions (see introduction). Such an empirical term has to be considered as the average effect of a, still missing, more complete model. For ohmic and L-mode cases (see [2] for a pinch model for hot ion H-modes) the values of D and V used are compatible with those derived from impurity transport just inside the separatrix [3]. The model works reasonably well at all densities up to detachment and provides the expected decay length of density at the mid-plane.

Profiles of J_s at the outer target computed with and without a pinch for the low recycling and high recycling phases of pulse #31627 are shown in figs 3 and 4. They indicate that at high density the profiles tend to be too broad even with a pinch, suggesting that the ratio V/D should perhaps not be spatially constant across the SOL.

Predictive simulations of several proposed JET divertor configurations (with the injection of nitrogen) show that the pinch model reduces the influence of the divertor geometry on the plasma SOL and target profiles. In all these cases the total radiated power and the distribution of nitrogen, considered as a recycling impurity, do not change strongly with the divertor geometry, a result which will be thoroughly tested in JET.

Comparison of T_e profiles from simulations and T_e profiles derived by probe theory from probe measurements show good agreement at low density but poor agreement at high density, particularly in the detached phase. In simulated detached plasmas T_e normally drops to 1-2 eV at the outer target and below 1eV at the inner target where recombination begins to play a role. These values are lower (sometimes by more than a factor of two) than those derived from probes. Standard probe theory may be incomplete and provide T_e too high in the regimes considered [4]. Whether this is a solution to the problem remains to be seen.

Spatial distribution of impurities

According to our simulations the distribution of impurities and impurity radiation depends upon the impurity that constitutes the main radiator, the degree of plasma detachment and the distribution of neutral impurity sources (particularly for intrinsic impurities like carbon).

In the case of carbon the zone of high impurity concentration and radiation moves away from the targets as detachment increases and the low temperature (≤7eV) zone extends. No bifurcation instability is observed, but above a certain level of radiation a small variation of radiated power implies a large variation of carbon content and the tendency to produce marfes. For example, simulations of the ohmic pulse #30829 show that with a total radiated power of 0.5 MW the plasma is well attached and the zone of intense radiation extends from the targets to just above the X-point. As the total radiated power exceeds 0.9MW strong detachment occurs and the zone of intense radiation moves above the X-point and tends to enter the plasma core. These trends are in agreement with experimental observations [5].

Conclusion

The route to detachment of ohmic and L-mode JET discharges is described reasonably well by EDGE2D/U, in particular if an empirical pinch model for particle transport is included. Important features such as the J_s roll-over and decline, the increase in D_α signals, and the general evolution of patterns of impurity density and radiation power density are reproduced.

However there are problems. For example the simulated spatial profiles of density and ion saturation current are too broad in the high recycling attached plasma phase (even with the pinch model). Also the details of simulated spatial impurity distributions differ from the experimental ones. Clearly the transport model and the description of impurity sources need to be improved for detailed predictions, but they already allow reasonable predictions of important general trends of divertor plasma properties.

REFERENCES

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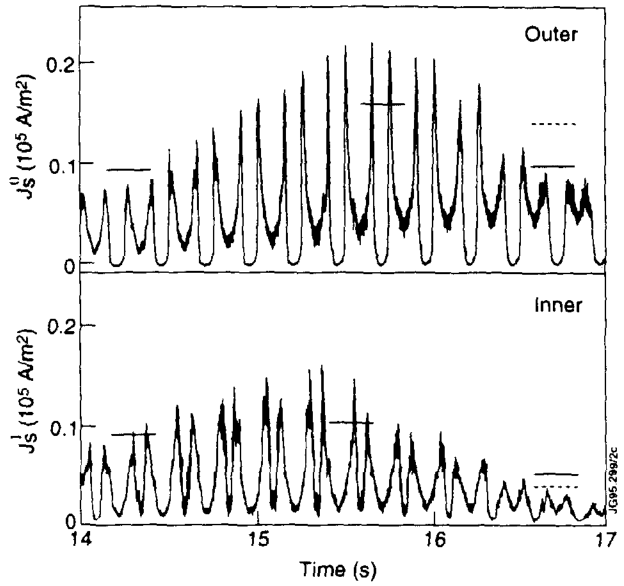

Fig. 1 Experimental and computed peak values of J_S at outer and inner targets for low recycling, high recycling and detached phase of ohmic shot 31627.

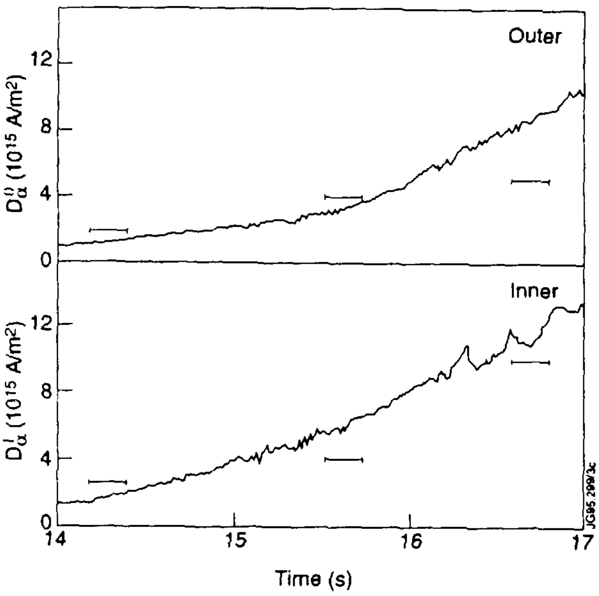

Fig. 2 Experimental and computed values of D_a signals for low recycling, high recycling and detached phase of ohmic shot 31627.

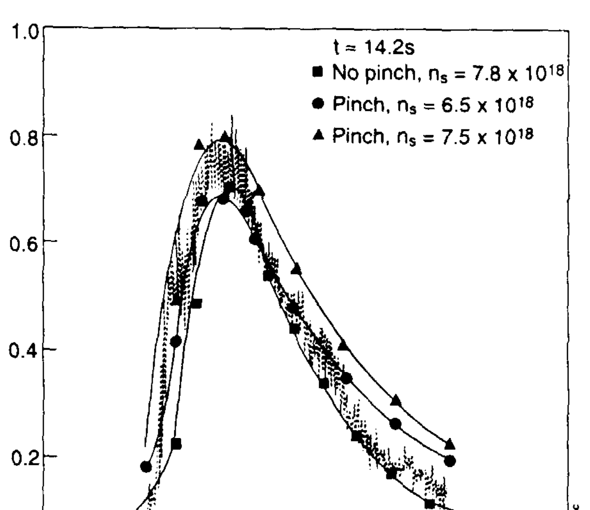

Fig. 3 Experimental and computed spatial profiles of J_S at outer target in the low recycling phase of ohmic shot 31627.

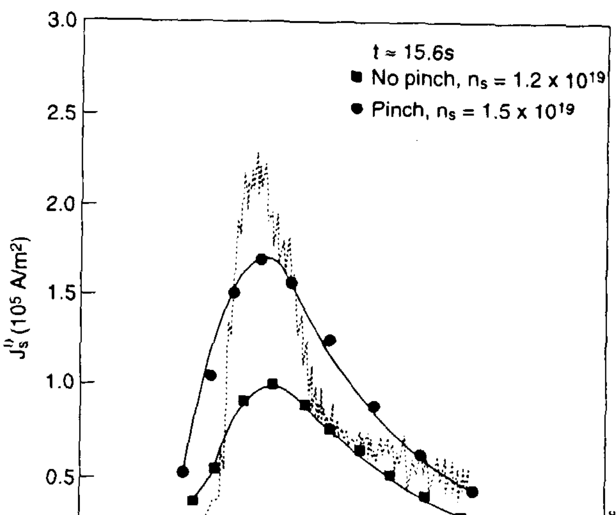

Fig.4 Experimental and computed spatial profiles of J_S at outer target in the high recycling phase of ohmic shot 31627.