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S. Wiesen, M.Wischmeier, M. Groth, W. Fundamenski, S. Brezinsek, V. Naulin
and JET EFDA contributors

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S. Wiesen[1], M.Wischmeier[2], M. Groth[3], W. Fundamenski[4], S. Brezinsek[1],
V. Naulin[5] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1] *Institut für Energieforschung - Plasmaphysik, Forschungszentrum Jülich, TEC,*
Association EURATOM-FZJ, Germany
[2] *Max-Planck-Institut für Plasmaphysik, EURATOM-Association, Boltzmannstr. 2,*
D-85748, Garching, Germany
[3] *Aalto University, Fusion Association-Tekes, Otakaari 4, 02015 Espoo, Finland*
[4] *EURATOM/CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*
[5] *Association EURATOM/RISØ-Technical University of Denmark, Roskilde, Denmark*
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ABSTRACT

A revised formulation of the perpendicular diffusive transport model in 2D multi-fluid edge codes is proposed. Based on theoretical predictions and experimental observations a dependence on collisionality is introduced into the transport model of EDGE2D-EIRENE. The impact on time dependent JET gas fuelled ramp-up scenario modelling of the full transient from attached divertor into the high-recycling regime, following a target flux roll over into divertor detachment, ultimately ending in a density limit is presented. A strong dependence on divertor geometry is observed which can mask features of the new transport model: a smoothly decaying target recycling flux roll over, an asymmetric drop of temperature and pressure along the field lines as well as macroscopic power dependent plasma oscillations near the density limit which had been previously observed also experimentally. The latter effect is strongest for scenarios with strike points on vertical targets and vanishes in case of asymmetric divertor configurations.

1. INTRODUCTION

Present multi-fluid modelling of time dependent transitions from an attached to detached divertor regime in tokamaks exhibits significant discrepancies when compared to experiments like JET, ASDEX-Upgrade [1], Alcator-CMod or DIII-D [2]. Among the experimental characteristics which cannot be satisfactorily simulated at a time are the following: a too rapid transition to detachment in the modelling, no significant ion flux roll over at the target plate as function of time and density, and no clear in-out target asymmetry in the degree of detachment. ITER, the next step fusion experiment, requires operation with partially detached outer target, and thus development and validation of simulation tools are necessary to make predictions concerning plasma operation.

A generic collisionality dependence on radial particle fluxes was observed experimentally [3-5], and the increase of intermittent radial transport as well as the reduction of the upstream parallel flow toward the target plates with increasing density was also predicted by fluid turbulence simulations, eg. [6,7]. However, the non-separability of the radial flux into effective diffusivities and velocities is critical in the interpretation of the experimental and simulation results: turbulent cross-field transport is of diffusive-advective nature and cannot be parametrised ab initio by an effective particle diffusivity and convection velocity [8].

Under the assumption that small-scale fluctuations can be averaged out, one can try to improve the understanding of macroscopic transport issues like the roll over into detached regime by heuristic parametrisations of transport. The transport model of the 2D fluid code package EDGE2D-EIRENE [9] has been modified to incorporate self consistently a collisionality dependence into the perpendicular diffusion coefficient and to account also for ballooning effects by applying a poloidal dependence.

This paper describes the impact of this modification in the discussion of time-dependent modelling of JET L-mode scenarios from attached divertor regime and the roll-over into partially/complete detachment. It is shown that an adhoc dependence of the radial diffusivity D on collisionality ν^* in some cases is sufficient to resolve some of the discrepancies between experiment and modelling.

It is shown that the plasma shape (strike points on vertical targets versus. asymmetric scenarios with open outer divertor) plays a strong role. Moreover, the new transport model in EDGE2D also predicts plasma solutions, whose dynamics near the density limit is similar to observations in earlier JET experiments [10]: the divertor conditions oscillate and the outer target re-attaches partially with a power-dependent frequency of a few Hertz.

2. DESCRIPTION OF TRANSPORT MODEL

EDGE2D solves the multi-fluid balance equations of particle, parallel momentum and energy for electrons and ions on a two dimensional grid. At the target plates the plasma is recycled by 100% whereas in the main chamber and private-flux zone an e-folding length parameter approximates the recycling fluxes from the wall. All plasma-wall interactions with the vessel and source terms to the plasma due to neutrals are provided by the kinetic Monte-Carlo code EIRENE. In EDGE2D the parallel transport is assumed to be of Braginskii form and no kinetic corrections in form of flux limiters are assumed. The Bohm-Chodura criteria at the target plates are applied. Perpendicular cross-field transport is described by particle diffusion, viscosity and heat conduction coefficients ($D_\perp, \eta, \chi_i, \chi_e$).

The newly introduced particle diffusion model consists of a modification of a reference $D_{\perp ref}(r)$ as function of collisionality ν^* ($\sim n_e/T_e^2$ taken at outer-midplane separatrix location) and a parameter α defining the strength of the dependence on the poloidal angle θ (with $\theta = 0$ at outer midplane):

$$D_\perp\,(r, v^*, \theta) = D_{\perp ref}\,(r) \bullet \left(\frac{v^*}{v_{ref^*}}\right)^{\varepsilon} \bullet exp\left(-\frac{In\ \alpha}{\pi^2} \bullet \theta^2\right) \tag{1}$$

The additional exponent ε adjusts the strength of the collisionality dependence. ν^* ref is a free parameter similar to $D_{\perp ref}(r)$ used to calibrate the model before pursuing with time-dependent simulations of density ramps. The modification to $D_\perp$ only applies in the SOL where the plasma is in direct contact with the targets. On closed field lines the transport is unaffected. In all simulations no modification to the heat conductivities has been applied, i.e. χ_i and χ_e are kept constant. A zero pinch velocity is assumed and no particle drifts have been included.

3. MODELING OF VERTICAL TARGET JET CONFIGURATION

A JET shot scenario with inner and outer strike points located both on vertical targets (based on JET Pulse No: 50401 equilibrum, cf. fig.1) was selected as a generica case. Parameters for applied power and gas-balance were selected as such that the evolving plasma density and temperature were in the typical JET operational space. For a given power entering the edge from inside the confined region (neglecting any dependence of ohmic heating on density) a time dependent increase of the gas fueling was used to drive up the particle content and to push the divertor from attached to high-recycling regime, following a roll over into complete detachment, ultimately exceeding the density limit threshold

The atomic physics model selected was simple: ionisation and recombination plus charge-exchange and molecular dissociation were included. Additional processes relevant for a more sophisticated modelling of high density divertors [11] as such as molecular assisted processes and elastic collisions were excluded here as well as impurities.

Figure 2 (left) displays time traces for the full transient from attached regime up to the density limit for the case with no collisionality or poloidal dependence assumed for the particle diffusion ($\varepsilon = 0$ and $\alpha = 1$). As the external fuelling increases in time both targets exhibit a long period where the plasma is attached to the plates as seen from a constant pressure along the field lines, $f_p = p^{down}/p^{up} \sim 1$, and Te falling only slowly. The radial width of the recycling flux at the target is increasing lightly, presumably due to redistribution via charge-exchange neutrals. After 5s T_e drops below 5eV and the peak of the particle flux has saturated. Suddenly, both targets experience an overall drop of T_e<2eV inducing strong volume recombination and the recycling flux drops sharply. Increasing the gas flux further the density limit has been reached although non-zero recycling fluxes are still observed.

The observation that both targets detach symmetrically is not supported by gas ramp experiments with vertical strike-point configuration. Rather it appears that the inner target detaches timewise at lower upstream density before the outer target. Inclusion of a collisionality dependency does help in that respect as seen in fig.2 (right). The increase rate of the gas-fueling ramp and the starting condition at t=0 are the same as in the case before (by selecting a suitable ν*ref keeping $D_{\perp ref}(r)$ fixed). The pressure and temperature are dropping towards the inner target at a lower gas-fuelling rate (at t~0.7s) as compared to the outer target where fp drops significantly not before t=1.5s indicating a longish partially detached phase lasting a few seconds. The recycling fluxes at the target is widening considerably across the plate and a smoothly decaying peak flux roll over occurs at both targets symmetrically in time, not dropping to zero. The phase of partial detachment at outer target seem to be rather stable up to the point where the gas fueling is strong enough to detach also the outer target fully (t=3.5s), following a density limit after another 0.5s.

4. OBSERVATION OF MACROSCOPIC PLASMA OSCILLATIONS

After a short period of increasing the gas-flux to a higher value the model normally responds with a density limit untreatable by the fluid-model description in EDGE2D. Interestingly, a certain grade of stability can be maintained when the plasma is driven by a lower power entering the edge. Figure 3 shows timetraces for the outer target for the case with linear ν*-dependence and with only half of the power applied as before. Whereas a case without ν*-dependence (not shown) behaves similarly as with higher power, i.e. it disrupts abruptly, the case with $\varepsilon = 1$ shows an oscillation between partial reattachment and detachment of the order of ~10Hz after t = 1.6s of the gas-fueling ramp. Numerical artefacts can be excluded here since the timestep in EDGE2D was controlled and kept always smaller compared to the parallel transport time of the order < 1ms, thus the oscillations seen in the modeling must be due to transport affecting the entire plasma solution. Similar observations of power dependent oscillations near the density limit have been observed previously at JET [10]. It has been reasoned that such macroscopic oscillations might be due to the wallrecycling of diffusing charged particles with spatially inhomogeneous transport coefficients [12]. Similarly, in EDGE2D we modify $D_\perp$ as prescribed by eq. 1 only within the SOL and not on closed fluxsurfaces. Additionally, a timewise variation of $D_\perp$ is provided by changes in the local separatrix quantities ne and Te constructing ν*, driven by the gas-fueling ramp. Thus we have a combination of a time and spatially dependent inhomogeneity in $D_\perp$. Whether this leads to a robust explanation for the occurrence of near density limit oscillations needs to be adressed in greater detail.

5. MODELING OF SHAPED JET PLASMAS IN HIGH-RECYCLING SCENARIOS, TRANSITION INTO DETACHMENT

Recent JET experiments had been pursued using a shaped equilibrium with low outer wall clearance where the X-point is in the vicinity of the inner vertical target and the outer strike point located on the horizontal target (cf.fig.1). The latter making the outer divertor rather open and hence strong leakage of neutrals into the outer main chamber is mandatory. Such geometrical features do lead to significant changes in the overall transition of divertor detachment which has been described previously [13]. Specifically, it was observed that the in-out asymmetry of the plasma roll over at the targets is affected considerably.

JET Pulse No: 78647 comprises of a stepwise density increase into the high recycling regime ($n_{spx} = 0.8$, 1.5 and 2.0 [$10^{19}m^{-3}$]). The low density case had been used to calibrate the transport model in EDGE2D-EIRENE. By matching the plasma profiles at the targets measured by probes and IRTV in combination with mid-plane profiles from high resolution Thomson scattering (HRTS) the reference transport model in EDGE2D-EIRENE has been set to $D_\perp^{ref} = 1.0\ m^2/s$ for $x < 0$ and $D_\perp^{ref} = 0.5\ m^2/s$ for $x > 0$ where x is the distance from separatrix (ν*ref has been set as such to make ν*/ν*ref = 1 for the low density case). All other transport parameters are similar to those described previosuly. But differently from above, intrinsic carbon impurities have been included by a combination of physical sputtering and a fixed chemical erosion yield of 1%.

It is observed that unexpectedly from the discussion in the previous sections, the qualitative and quantitative best fit was reproduced for the case where actually no ν*-dependence ($\varepsilon = 0$) was assumed. In case of $\varepsilon = 0.5$ the highest density ($2.0\times10^{19}m^{-3}$) was not achieved since a plasma roll over at the outer target was already seen at $n_{spx} = 1.9\times10^{19}m^{-3}$ and in case of $\varepsilon = 1$ the rollover occurred at even lower densities.

The gas fuelling in EDGE2D-EIRENE simulations has been further increased to induce subsequent roll over and an artificial transition into detachment (JET Pulse No: 78647 exhibited no detachment transition). From figure 4 one can conclude that a rather open outer divertor configuration leads to the fact that the target detaches in terms of T_e and f_p from the far-SOL moving inwards rather starting from the strike point moving outwards. The ion flux on the other hand is still rolling over at the strike-point location which is experimentally observed either [14]. At the inner divertor a secondary recycling flux footprint emerges at the inner baffle as soon as f_p and T_e dropped significantly across the outer target. The additional inner baffle flux spot seems to be responsible for stabilising a period of semi-detachment. As the density increases further and beyond inner-target detachment, a density limit occurs quickly without any oscillative features.

From the timeplots of target fluxes shown in figure 5 it is clear that with increasing ε firstly, the roll over occurs at a lower upstream density, and secondly, the flux is dropping to near-zero values. An explanation for this could be derived by the fact that intrinsic impurities are included here: carbon and its radiation are responsible for levelling up the density in front of the target plates before the roll over. As Te drops the chemical erosion and physical sputtering decreases [15] reducing the target density and thus the particle flux efficiently.

Without collisionality dependence ($\varepsilon = 0$) the flux saturates at high densities rather than rolling over and drops off suddenly, causing EDGE2D to become unstable. When pushing the density even higher the occuring flux roll over is still symmetric between inner and outer target. A tentative introduction of a ballooning factor into the transport model as previosuly suggested [16] does not improve either as seen for the case with $\varepsilon = 0.5$ and $\alpha = 0.1$ (10 times less particle diffusion at the inner midplane compared to the outer). The decrease of $D_\perp$ at the inboard side increases the separatrix density at both the inner and outer midplane due to an overall decrease of radial transport. At the same level of gas fueling this means that the outflow $\Gamma^{plate} = n^{plate} v^{plate}$ to the targets has to increase stronger. A secondary consequence is the roll over of the upstream density occuring at a higher gasfueling rate. A timewise in-out asymmetry of the roll over on the other hand is still not seen.

CONCLUSIONS

Following the predictions from turbulence transport theory the introduction of a collisionality dependence on the radial transport has been introduced in 2D multi-fluid edge modelling. In the assessment of the time-dependent transition from an attached divertor into a detached regime a smoothly decaying recycling flux roll over at the target plates is observed which is actually dropping to zero. The roll over happens at lower densities when compared to previous modelling attempts. The temperature and pressure drop along the field lines exhibits now an in-out asymmetry. Finally, global plasma oscillations near the density limit do occur which had been previously observed by the experiment too.

Whilst we see these promising results one issue is still left: the particle fluxes roll over at the targets does not exhibit an in-out asymmetry. Whether this is due to geometric effects obviously playing an important role, missing cross-field drifts in the current analysis or other transport features not included in the modelling is not clear at this point.

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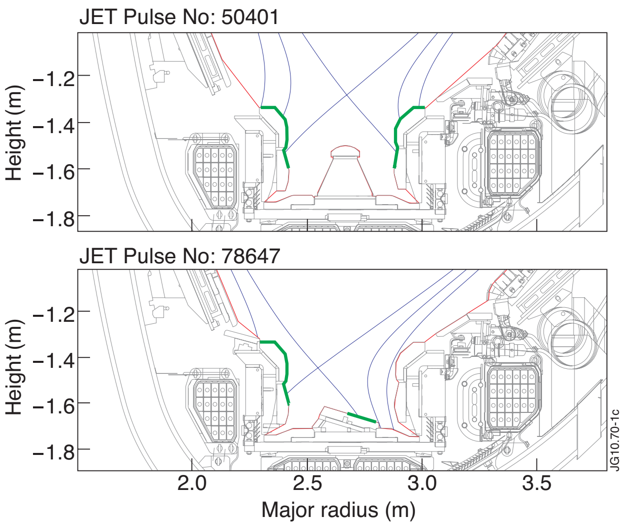

Figure 1 : JET Pulse No's: 50401 and 78647 divertor geometry. Target locations modelled shown in green colour.

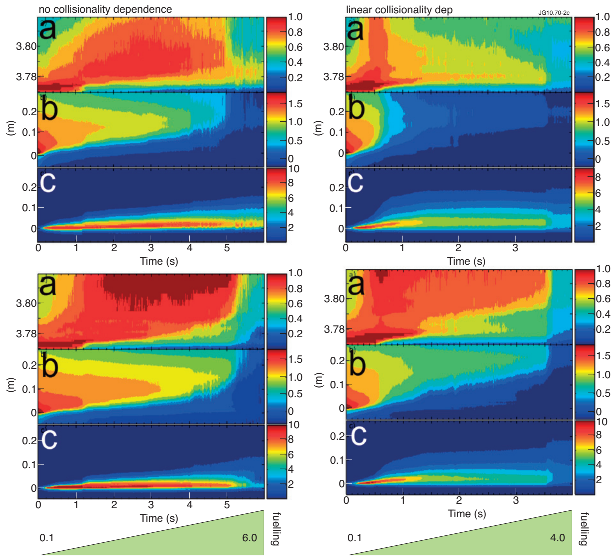

Figure 2 : Time traces for JET Pulse No: 50401 7MW gas-fueling ramp in 1022 el/s. a) relative pressure ratio $f_p = p^{down}/p^{up}$ mapped to outer mid plane, b) log $T_e{}^{plate}$ and c) target recycling fluxes Γ^{plate}. Profiles in b),c) along target plate as depicted in fig.1 (separatrix at 0). Top: inner-, bottom: outer target. Left: no collisionality dependence ($\varepsilon = 0$), right: linear collisionality dependence ($\varepsilon = 1$).

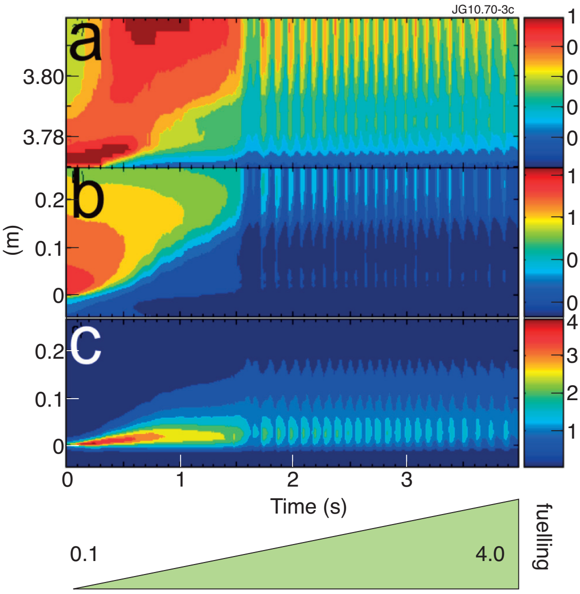

Figure 3 : Time trace of case $\varepsilon = 1$ as in fig 2 but with half the power applied (3.5MW). Only outer target shown.

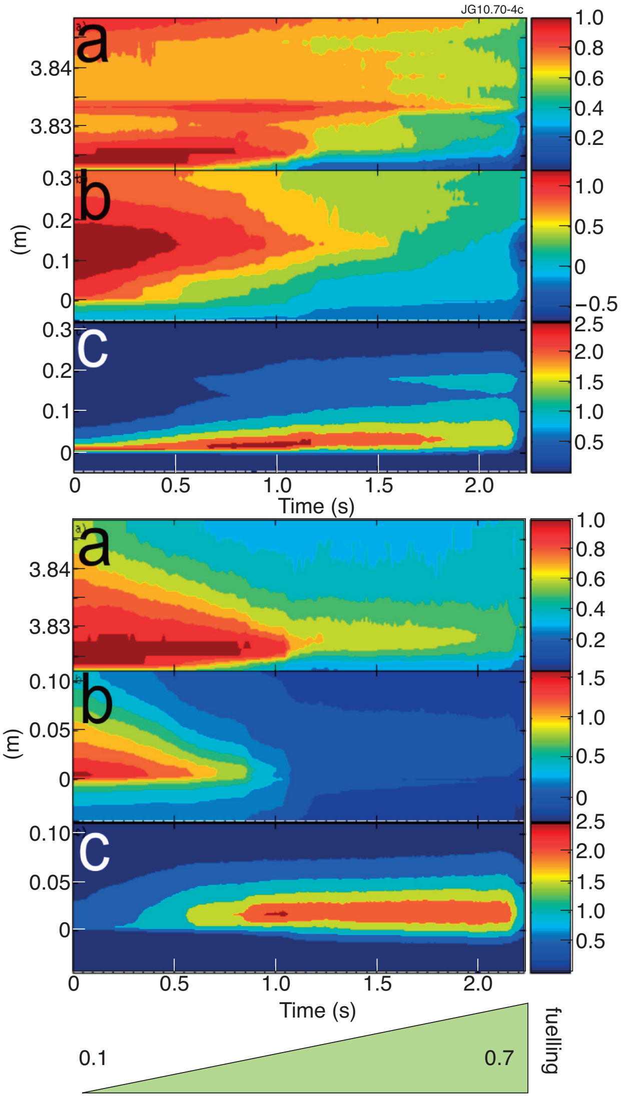

Figure 4 : Time traces for the JET Pulse No: 78647 (layout as in fig.2) for the case $\varepsilon = 0$ *and* $\varepsilon = 0.1$.

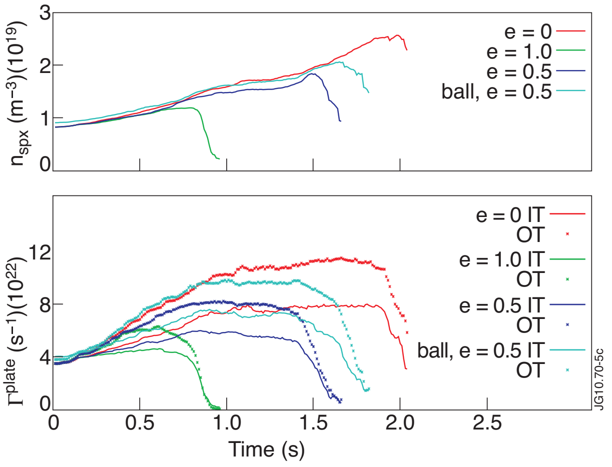

Figure 5 : n_{spx} *and* Γ^{plate} *as function of time for modelled JET Pulse No: 78647 artificially pushed into detachment by increasing gas fueling in EDGE2D-EIRENE. Red, blue and green:* $\varepsilon = 0$, $\varepsilon = 0.5$ *and* $\varepsilon = 1.0$ *respectively. Solid lines: inner target, symbols:*