An exploration of a low temperature regime in EDGE2D-EIRENE simulations of JET ITER-like wall L-mode discharges

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1. Introduction

JET, with its ITER-like wall (ILW) of Be in the main chamber and W in the divertor, is ideally suited to studies in understanding the behaviour of the plasma edge and divertor, essential for predicting the performance of next-step machines such as ITER. Simulations by Groth *et al.* [1] of L-mode discharges run during JET-ILW campaigns and previous JET-C ones, in which the plasma-facing surfaces were predominately C, have consistently shown a shortfall in the radiated power at low temperatures below that measured by bolometry. This brings into question predictions for the radiated power and cooling of a radiative divertor in a next step-machine. Similar results are found for unseeded ELMy H-mode discharges by Järvinen *et al.* [2]. A series of JET-ILW L-mode discharges, which reach detachment, provide a stringent test of the simulations in that most (~90%) of the radiated power from the divertor is due to atomic and molecular D, with impurities only playing a small role. In the present EDGE2D-EIRENE [3] simulations, the molecular densities show significant variations from less than ~5% to approaching those of the atomic densities. The various emissions possible from the D_2 molecules are discussed by [4,5]. To investigate the atomic contributions to the radiated power with the aim of distinguishing between the effect of the atoms and transport, the simulations are compared with an independent atomic physics model, a preliminary one being available for He II. It is noted that the behaviour of D is very similar to that of He II, the D features occurring at a somewhat lower T_e (by ~2 eV). Crucially, the model must be complete and self-consistent.

2. Simulations

The EDGE2D-EIRENE simulations are based on the JET-ILW, L-mode simulations of Groth *et al.* [1]. They apply to a density scan series of 2.5MA / 2.5T discharges, pulses 81472 – 81492, heated with 1.1, 1.2 or 1.6 MW of NBI, which reach detachment. The simulation geometry is taken from discharge 81472, the fuel being D with Be and W impurities. Outer midplane separatrix densities from 7×10^{18} m^{-3} up to the maximum at which the simulations converge (2.0-2.2$\times10^{19}$ m^{-3}) were considered, while the transported power across the separatrix into the SOL ranged from 2.2-2.8 MW. Little sensitivity to the power crossing the separatrix was found, and hence the study has concentrated on the 2.2 MW simulations. The version of the EDGE2D-EIRENE code used explicitly includes D_2^+ molecules with molecular assisted processes such as MAR. Kotov *et al*. [6] details the full reference atomic and molecular datasets employed. The simulations use a diffusive transport model, with radially-varying particle and thermal diffusivities as illustrated in figure 9 of [1]. These were determined for the lowest density case, the same model being used for the higher density simulations. Ballooning transport and cross-field drifts are not included in the present simulations, although the latter are discussed by [7,8]. For the present cases, drifts increase the radiated power by at most 30%, this decreasing with increasing density. To obtain results that fall in the low temperature regime, the atomic and molecular power loss terms have been artificially increased as described by [9]. In that case the terms were increased using quadratic polynomials in T_e, but more control and flexibility is achieved by increasing the order of the polynomial used to quartic. By increasing the atomic power loss term by at most 4% in the temperature range 10-30 eV, T_e was reduced by up to ×10. In this way, low temperature simulations were achieved and a series of cells along a flux surface (ring) selected in which T_e varied from 0.29-21.2 eV.

3 Atomic physics model

Stand-alone atomic physics models are being developed for D I and He II [10] that consider the dominant populating channels for energy levels in these hydrogenic species, including electron and heavy particle collisional excitation and deexcitation, radiative decay, direct electron collisional ionization, radiative and three-body recombination as shown in figure 1. The models allow all components of the radiated power to be determined, particularly the total power and line radiation from the 'spectroscopic' levels within the n=1-5 shells (n the principal quantum number), which can be directly compared with experiment. Indeed, Ly-α radiation is expected to account for ~85-90% of the power radiated by these H-like species over a wide temperature range. A J-resolved description (J the total angular momentum) is used for the spectroscopic levels and n-resolution for higher shells up to the maximum considered of n=16. This is above the collision limit for these species at all densities of interest, where the probability of the atom being ionized exceeds 50%. Currently the He II model is being tested. Values of T_e, n_e, n_D, n_{D+} from the simulations are interpolated to the temperatures used by the model (figure 2), and then used as model inputs.

4 Results

Figure 3 compares the radiated power due to atomic D output from the EDGE2D-EIRENE simulation with results from the He II model. Different populating channels can be readily switched on or off in the model. It is found that removing radiative recombination as a populating mechanism makes comparatively little difference, since three-body recombination has a much larger effect, this channel strongly feeding the high *n* shells. At present it is not known whether this effect is overestimated, which leads to uncertainties in the model results at the lower temperatures. Nevertheless, the model clearly shows an increase in the radiated power below T_e ~3 eV, as recombination plays an increasing role in populating the excited levels and in direct contributions from radiative recombination. A similar increase is expected for D I. The importance of recombination at low temperatures is best illustrated by removing recombination from both the model and the simulation, the excited levels being populated only by collisional excitation from the ground state. In both cases (figure 3) the radiated power is seen to fall steeply with T_e, the D I simulation results being at ~2 eV lower temperatures. With recombination, the simulated D radiated power is approximately maintained with decreasing T_e. This results in a significant shortfall compared to the He II model, illustrated by the ratio of the modelled to simulated radiated power in figure 4.

As with other fluid transport codes, the radiation is calculated in the fluid, in this case the EDGE2D, section of the code. For recombination this is done using the recombination-bremsstrahlung power coefficient, PRB [11]. The PRB term together with the collision-radiative recombination coefficient, ACD, are also used to calculate changes to the electron energy loss term due to recombination. However, combining radiative recombination, bremsstrahlung and three-body recombination into coefficients that can only be positive presupposes that the former always dominate three-body recombination. Radiative recombination and bremsstrahlung lead to an energy loss, whereas three-body recombination to an energy gain. In the simplest case of radiative recombination to the ground state, the electron energy loss is the kinetic energy of the recombining electron. Three-body recombination is the reverse reaction to collisional ionization, which has an energy loss, say, from the ground state of the D ionization potential, I_H, and a corresponding energy gain of I_H for three-body recombination to the ground state. That radiative recombination always dominates three-body recombination is not confirmed by the present, preliminary results.

5 Conclusions

A strong dependence of the atomic power loss term on T_e in EDGE2D-EIRENE simulations has enabled a low temperature regime to be accessed, allowing a comparison with a preliminary stand-alone atomic model. Radiation is treated in the EDGE2D, two-fluid transport code and a significant shortfall is found in the simulated D radiated power below that expected from the atomic model. Work is in progress to understand this result, which should largely account for the radiated power discrepancy found at low temperatures in these simulations.

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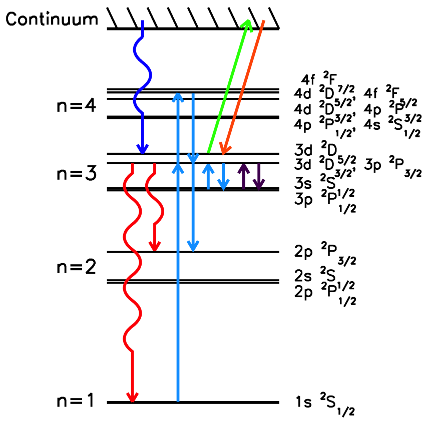

Figure 1. Schematic diagram of the hydrogenic energy levels showing populating and depopulating channels. These include radiative decay, electron and heavy particle collisions, direct collisional ionization, radiative recombination and three-body recombination.

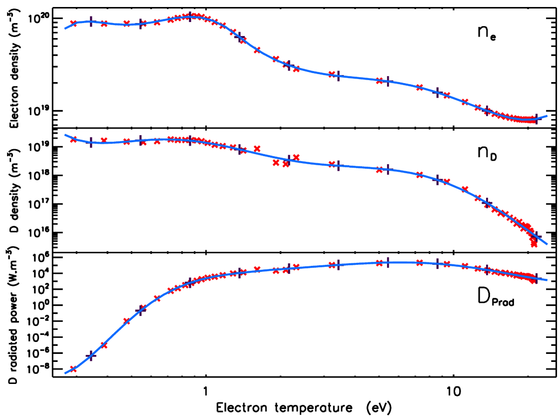

Figure 2. × D simulation output of $n_e \approx n_{D+}$, n_D, D_{Prad} from cells along a flux surface, showing interpolations and + points used as inputs for the model or for a comparison with P_{rad}.

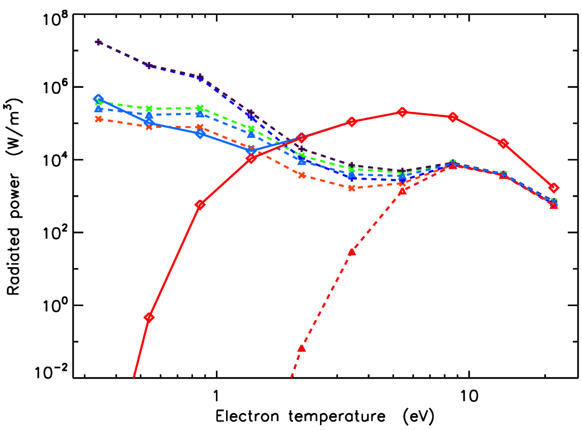

Figure 3. Radiated power from ◊ D simulation and ◊ excluding recombination, + He II population model and + excluding radiative recombination radiation, × population model excluding 3-body recombination rate and × excluding radiative recombination radiation, Δ population model excluding radiative and 3-body recombination rates and Δ excluding radiative recombination radiation.

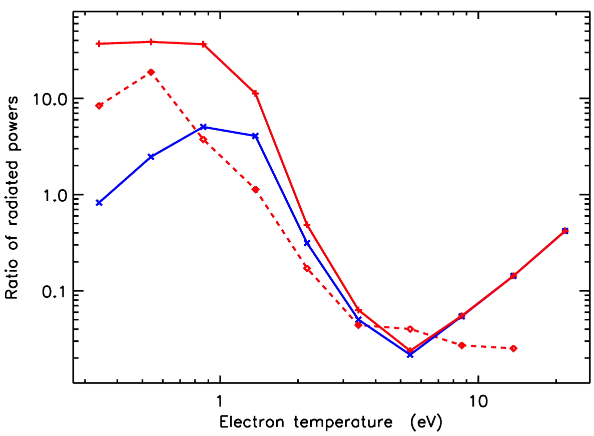

Figure 4. Ratio of He II modelled to D simulated radiated powers. + full population model, × population model excluding 3-body recombination rates, ◊ full population model shifted by one temperature interval to account for use of He II.