Influence of Plasma Composition on Divertor Detachment

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Abstract

The phenomena that lead to the observed power and particle flux detachment have been studied with the code B2-Eirene for DIII-D Helium and Deuterium experiments. Contrary to the usual Deuterium experiments, a significant reduction of the power load to the divertor is observed in Helium discharges while the ion flux remains high. Modelling indicates that this is due to the longer ionisation mean free path of Helium, which can penetrate from the divertor into the bulk plasma with the consequent power loss. At this stage of Helium detachment, most of the outer divertor plasma remains at an electron temperature of $\sim 5-10$ eV, for which Helium recombination does not occur.

1 Introduction

The problems of heat load and erosion on first wall materials have been identified as one of the main areas to be addressed in the design of existing divertor experiments and next step devices. Presently, the favoured solutions to these problems are based on the extrapolation of the radiative divertor regimes observed in experiments, where volumetric losses reduce the power and particle flux to the target achieving the so-called detached divertor regime. The physics of plasma detachment is crucially influenced by atomic physics processes, chiefly charge-exchange, recombination and radiation, to which the ions and neutrals of the main ion species, as well as the impurities, are subject [1,2]. In order to determine the relative importance of these processes experimentally, a series of experiments in similar Deuterium and Helium plasmas was performed in the DIII-D tokamak [3]. The main outcome of such experiments was that in Helium plasmas, contrary to Deuterium, it is possible to achieve a regime of power detachment, while the particle flux to the divertor remains high (no particle flux detachment). This paper presents a study of such experiments with the 2-D multifluid B2-EIRENE code [4], which includes all relevant atomic physics processes in the SOL and divertor both for Helium and Deuterium plasmas.
2 Experimental data

The experiments considered are L-mode plasmas with ~2 MW of additional heating in which density ramps are performed by gas puffing. Fig. 1 & 2 show the midplane electron pressure and temperature profiles for such an experiment, at several stages of divertor detachment. Fig. 3. & 4. show the corresponding power and particle flux to the outer divertor strike zone for the same time slices as of Fig. 1 & 2. The labelling of the divertor detachment state follows the convention used in DIII-D, based on the power flux measurements [3]. From the first (1640 ms) to the second (2000 ms) time-slice the main plasma density increases from 5.0 to $6.5 \cdot 10^{19}$ m$^{-3}$ and finally (2410 ms) to $7.5 \cdot 10^{19}$ m$^{-3}$. In such density ramps, it is seen that the power flux to the divertor decreases with increasing density, while the particle flux remains basically unchanged (but for a region close to the separatrix inside the private flux region) [3]. Then, at the highest density, the power flux decreases further and the region of high particle flux in the private flux region disappears. It is worth pointing out that the particle flux remains at values comparable to the low density time-slice even at the highest density. The SOL temperature and pressure show a clear decrease for the highest density time-slice (2410 ms).

3 B2-Eirene modelling

B2-Eirene modelling for such experiments and comparable Deuterium discharges has been carried out. The model contains accurate descriptions of most of the relevant atomic/molecular reactions for plasma detachment (charge-exchange and plasma recombination) both for Deuterium and Helium plasmas. However, no molecular activated recombination processes have been included in these studies [5]. These molecular catalysed processes may play a role in the Deuterium experiments but not in the Helium discharges, where the concentration of Deuterium in the divertor was found to be negligible (<1%) [3]. Modelling without and with Carbon impurities has been performed. Carbon is assumed to be produced by physical sputtering in Helium plasmas and by physical + chemical sputtering (1% constant yield) for Deuterium plasmas. At high densities carbon is responsible for most of the radiation (70%) (Fig. 5) in
Deuterium plasmas, while it plays no role in Helium plasmas. At high densities the divertor plasma near the strike point reaches very low electron temperatures at which physical sputtering is negligible (Fig. 6).

![Graph](image1)

Fig. 3: Outer divertor parallel power flux in DIII-D Helium density ramp experiments.

![Graph](image2)

Fig. 4: Outer divertor parallel particle flux in DIII-D Helium density ramp experiments.

![Graph](image3)

Fig. 5: Radiated power proportion versus separatrix density for the B2 runs.

![Graph](image4)

Fig. 6: Divertor electron temperature versus separatrix density for the B2 runs.

As shown in Fig. 7, with increasing density the power that reaches the divertor decreases both for Deuterium and Helium plasmas and, together with it, the electron pressure at the divertor (Fig. 8). Only for Helium plasmas, there is a clear decrease of the SOL electron pressure for the highest density cases, which will be discussed later. In spite of the drop in divertor power flux and pressure, the particle flux continues to increase with density up to the highest density runs, in which is seen to decrease (both for Helium and Deuterium simulations) (Fig. 9). The decrease of the ion flux in Deuterium is associated with the achievement of very low divertor temperatures (∼1 eV) (Fig. 6), for which significant recombination can take place in the divertor (Fig. 5.b). For Helium, however, the temperature reached is ∼3 eV (Fig. 6) and no significant recombination takes place even at the highest densities (Fig. 10).

This dramatic difference between Deuterium and Helium both in the experiment and the calculations can be understood by examining the electron temperature and
ionisation/recombination losses for Deuterium (Fig. 11 & 12) and Helium runs at the highest densities (Fig. 13 & 14). Despite the very low divertor temperatures (Fig. 11) achieved in the Deuterium runs and the strong recombination (Fig. 12), the Deuterium neutral penetration inside the separatrix is small and, as a consequence, no significant ionisation losses inside the separatrix are produced, even at this advanced stage of plasma detachment. For the Helium runs, the picture is just the opposite (Fig. 13 & 14). There is strong cooling of the plasma inside the separatrix, because of neutral Helium penetration through the X-point, even when most of the outer divertor remains at a reasonably high temperature (∼5-10 eV) (Fig. 13), at which no Helium recombination takes place (Fig. 14).

4 Conclusions

Modelling of Helium and Deuterium discharges in DIII-D with B2-Eirene has demonstrated that in the evolution towards detachment the pressure drop from the SOL to the divertor (driven by charge-exchange momentum losses) occur simultaneously both
for Helium and Deuterium. However, from this point on, the detachment evolution is very different for Helium and Deuterium. For Deuterium, the divertor plasma reaches very low temperatures that cause strong recombination, leading to the decrease of the divertor particle flux. For Helium such a regime cannot be achieved because, before
the divertor can reach the low temperature necessary for recombination, significant Helium penetration through the X-point leads to the collapse of the bulk plasma. This produces the observed decrease of the particle flux without recombination, in agreement with previous experiments carried out in ASDEX-Upgrade [6].

References