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Studies of detached plasmas on the ULS divertor simulator

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Abstract

We report on studies of detached plasma operation in the UMIST linear system (ULS). The ULS, designed to study a range of edge physics issues relevant to tokamak divertors, is capable of producing plasmas with electron densities and temperatures in the range 10^{17}–10^{19} m^{-3} and 2–15 eV, respectively. Previous studies of the interaction between the hydrogen plasma and low-pressure hydrogen gas have identified a regime where molecular activated recombination (MAR) processes dominate plasma losses. Here we report on studies in which the upstream plasma parameters are varied such that three-body and radiative electron–ion recombination (EIR) dominates. Initial modelling of the recombination region is undertaken using a simplified version of the one-dimensional electron energy and continuity equations. We determine the factors that govern the threshold between MAR and EIR dominated detached regimes in terms of upstream plasma parameters and compare this with predictions based on the competing effects of electron cooling and recombination.

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1. Introduction

The study of plasma-neutral interactions at the edge of fusion related devices has attracted increasing interest, particularly with regard to understanding 'detached' divertor plasmas. Detached plasmas [1] are characterised by low electron temperatures, substantial pressure gradients along magnetic field lines and a dramatic reduction in the flux of ions and power to divertor target plates. Studies on a number of tokamaks (e.g. [2,3]) have demonstrated the existence of significant plasma recombination processes in detached plasmas. Although the role that volume recombination plays in the mechanism of detachment is uncertain, an understanding of the balance of ionisation and recombination in divertor plasmas is important. In addition to three-body and radiative electron–ion recombination (EIR), much interest has recently been concerned with the significance of molecular activated recombination (MAR) [4]. This involves the capture of electrons by excited hydrogen molecules followed by dissociation into hydrogen neutrals and negative ions and finally charge exchange between those negative ions and plasma ions: the overall effect is to raise the electron temperature at which recombination dominates ionisation.

Alongside tokamak research, measurements on linear confinement machines have been of increasing interest in studies of detached plasmas and have helped in elucidating the physics of plasma-neutral interactions [5]. Results from the UMIST linear system (ULS) [6] have shown that a reduction in the flux of a plasma beam is observed when it interacts with a hydrogen gas target at modest pressure (2–8 mTorr). An analysis of these results led to the conclusion that, in contrast to recent results from PISCES A [7], cross-field transport was not a significant factor in determining this reduction in flux, which was instead attributed to MAR processes.

Here we present further studies on the ULS in which we examine the transition between MAR and EIR

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dominated plasmas. By varying the upstream conditions it is possible to move from a MAR dominated plasma to a regime where EIR becomes the main plasma loss process. We present Langmuir probe and spectroscopic results of the resulting recombining plasmas and consider the parameters that determine the threshold between MAR and EIR regimes.

2. The UMIST linear system

Fig. 1 shows a diagram of the ULS. The vacuum vessel (≈1.5 m long) is divided by a diaphragm containing a small orifice to separate off the gas target chamber from the upstream chamber. The plasma source is a development of a 'duoplasmatron' used previously by the UMIST group: these typically have high ionisation efficiencies, although tend to produce plasmas characterised by supersonic ion velocities [6]. For the work reported here the gradients of electron temperature and density in the upstream chamber are characterised by scale lengths of the order of 1–3 m, typically an order of magnitude greater than the equivalent scale lengths in the gas target chamber.

Reciprocating Langmuir probes allow the acquisition of radial profiles of electron density and temperature at various positions within the target and upstream chambers. In addition a probe inserted from the end target plate allows axial profiles of density and temperature to be measured in the target chamber. Finally it is possible to measure the current to the target plate, providing a measure of the degree of detachment. The plasma spectral emission is monitored over the range from 800 to 6500 Å: two spectrometers (VUV and UV/visible) are employed allowing simultaneous monitoring of different spectral regions of the same plasma volume.

3. Characterisation of EIR dominated plasmas

Earlier work [6] has given details of the plasmas resulting from MAR processes: here we present a characterisation of EIR dominated plasmas. If the plasma source parameters are changed such that the upstream plasma density is raised and the upstream electron temperature is reduced compared with the MAR dominated regime, it is possible to alter the mode of recombination. In this case the plasma is terminated in a blue 'flame' like region of approximately 5–10 cm in length. Fig. 2(i) shows results from axial Langmuir probe measurements of electron temperature and density in the gas target chamber for these plasmas. As the electrons cool, it is seen that the electron density remains more or less constant. The localised rise in electron temperature at approximately 12 cm from the orifice is believed to be result from a shock front forming at this point: plasma potential measurements around this region suggest a double-layer structure possibly due to the supersonic ions from the upstream plasma being slowed to sub-sonic velocities. Beyond this feature, as the temperature falls to below about 1 eV and coincident with the region of strong light emission, the electron density decreases

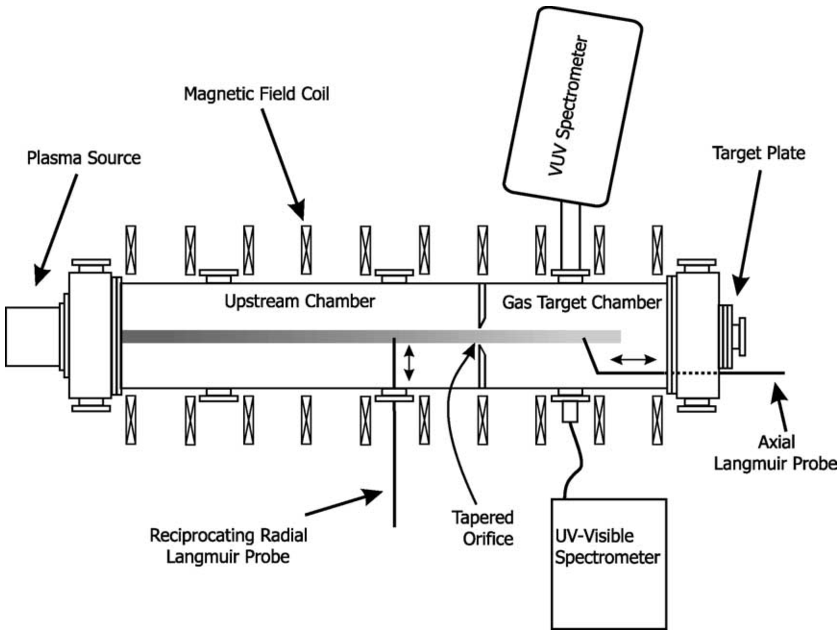

Fig. 1. Schematic diagram of the ULS showing gas target chamber and positions of Langmuir probe and spectroscopic diagnostics.

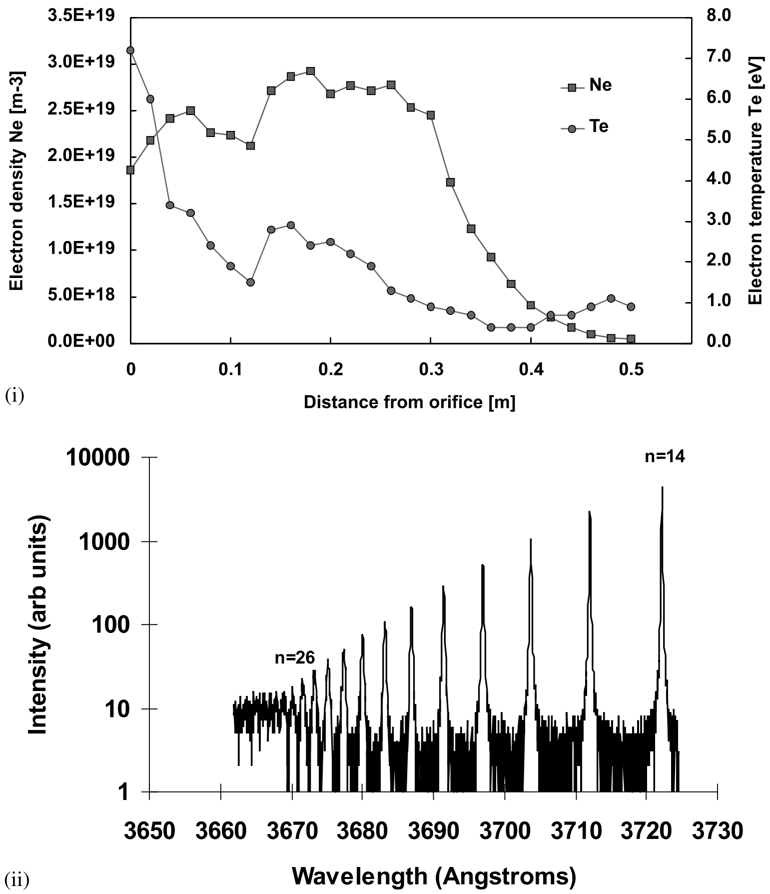

Fig. 2. (i) Axial profiles of electron density and temperature in the gas target chamber for an EIR dominated plasma showing a strong reduction in density as the electron temperature falls below 1 eV. (ii) Hydrogen Balmer series spectral lines showing emission from high n states, characteristic of EIR.

dramatically over a distance of 5–10 cm. Spectroscopy of this shows the characteristic highly excited states of the hydrogen Balmer series expected of EIR (see Fig. 2(ii)). An analysis of the continuum radiation around the series limit suggests an electron temperature of approximately 0.1 eV, considerably lower than that from the Langmuir probe measurements. Although Langmuir probe diagnostics can give overestimates of temperature [8] in detached plasmas, for these experiments the disparity between the two values is mainly due to the limits of resolution of the probe data acquisition system and the temperatures determined spectroscopically are regarded as being more indicative of the true plasma conditions in the EIR dominated region.

As an initial approach to modelling the axial plasma profiles in EIR dominated plasmas, we consider a simple 1D model [9] including electron cooling due to collisions with cold ions (assumed to be equilibrated with the neutral gas) and a diffusive plasma flux with particle loss by recombination. We solve the fourth order set of equations

$$\frac{d}{dx}\left(\kappa_e \frac{dT_e}{dx}\right) = \left(\frac{3}{2}\right) \nu n_e (T_e - T_N),$$
$$\frac{d}{dx}\left(\frac{1}{M\nu_{iN}} \frac{dp}{dx}\right) = (\nu_{EIR} + \nu_{MAR}) n_e,$$

where κ_e is the electron thermal conductivity, ν is the electron–ion equilibration frequency, ν_{iN} is the ion–neutral collision frequency, ν_{EIR} and ν_{MAR} are the molecular activated and EIR frequencies respectively. We initially neglect MAR processes and assume that the neutral temperature, $T_N = 0$. The equations are solved using a Runge–Kutta algorithm, with sheath boundary conditions at the target plate. Fig. 3 shows a range of density and temperature profiles for fixed upstream temperature and varying upstream density. It is clear that the general form of the detached plasmas is reasonably well reproduced even with this simplified model. For example, the lowest two curves in Fig. 3 (labelled (d) and (e)) show a distinct detached region, with low $T_e \approx 0.01$ eV and a sharp drop in density in the region where sufficiently low temperatures for EIR are

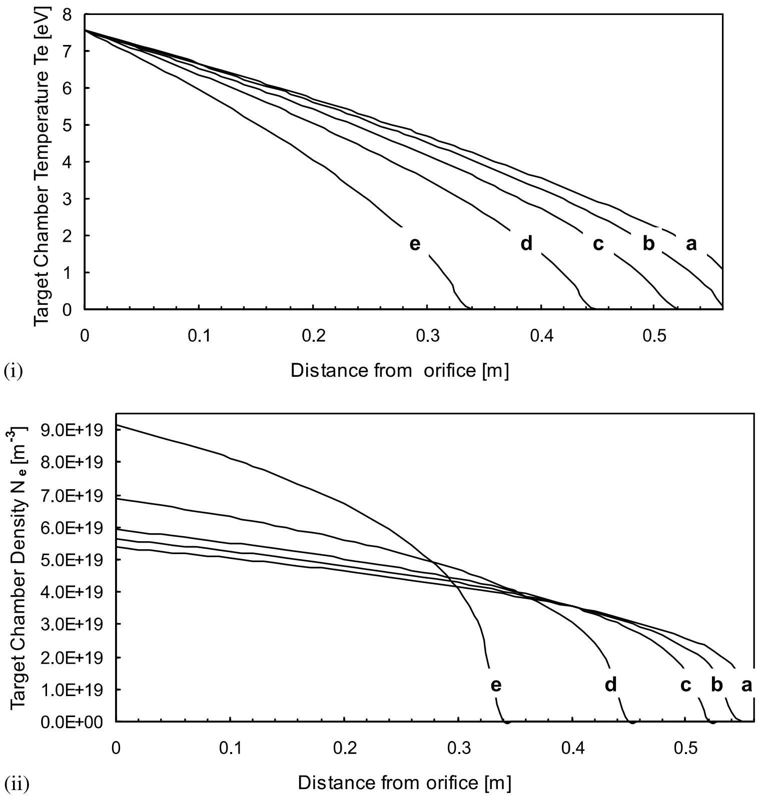

Fig. 3. Axial profiles of electron temperature (i) and density (ii) in the gas target chamber predicted by simple 1D model with fixed upstream temperature, $T_u = 7.5$ eV and a range of varying upstream densities, $n_u = 5.4\text{–}9.1 \times 10^{19}$ m^{-3} (a–e).

obtained. Some care must be taken in identifying a drop in density with recombination – in fact, recombination is negligible for the whole of the upper two curves in Fig. 3, in the sense that the flux ($j = (1/\nu_{iN})(dP/dx)$) is almost exactly constant. However, there is a significant drop in flux associated with the above mentioned recombination regions for the lower curves. The extent of the recombination can be seen to increase with increasing upstream density.

4. Dependence of threshold between MAR and EIR regimes on upstream plasma parameters

Having inferred the presence of both MAR and EIR dominated regimes in the ULS, a study of the dependence of the mode of plasma recombination on upstream plasma parameters (temperature T_u and density n_u) was undertaken. In this case, 'upstream' refers to parameters in the main chamber, away from the main region of plasma-neutral interaction: in a tokamak this corresponds to regions of the SOL some distance from the divertor target plate. Experimentally it is found that the source output is dependent on a number of external factors: for example, magnetic field strength, source gas flow, source arc current, etc. To fully explore the operating space of the source, all of these factors were varied over as large a range as possible so as to obtain a full operating space diagram for the source. With a fixed gas target pressure of 8 mTorr, it was found that for all of the conditions obtained, the plasma was detached from the end target plate: the range of degree of detachment (defined as the total plasma flux to the target divided by the flux through the orifice) was in the range $\leqslant 0.05$–0.1 for all cases.

Spectroscopic monitoring of the plasma in the target chamber was used to determine the mode of recombination. Fig. 4 indicates that there is a distinctive boundary between the regions of parameter space in which the two modes of recombination are obtained. A simplified analysis by Krasheninnikov [9] suggests that the dominance of EIR over MAR is the result of competing effects of recombination and collisional electron cooling. We thus find a simple analytical expression for the threshold between the EIR and MAR of the form $T_u = Cn_u^{2/3}$ ($C = 1.04 \times 10^{-12}$ is a constant derived from the relevant rate constants, assuming a temperature independent rate for MAR). This is also shown on Fig. 4: the agreement is reasonable but clearly a more detailed

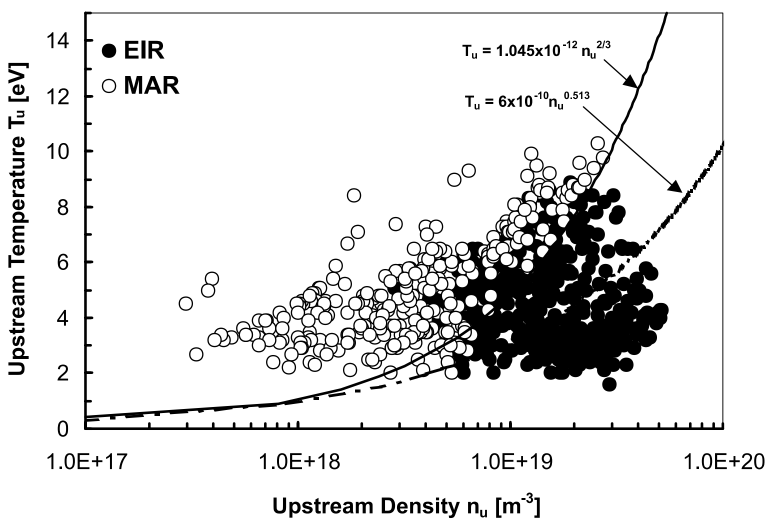

Fig. 4. Mode of recombination for detached recombining plasmas in the ULS in upstream n_e–T_e parameter space. The solid line indicates the form of the predicted threshold expected for a simple model based on the competing effects of collisional cooling and recombination. The dashed line indicates the modelled threshold between attached and EIR dominated detached plasmas.

analysis is required for fuller understanding. Finally, even though it does not explicitly include MAR effects, it is instructive to consider the threshold between attached and EIR dominated detached plasmas. The model outlined in the previous section predicts a sharp threshold for onset of EIR as the upstream conditions are varied; for example, the curves in Fig. 3 show, that for a fixed upstream temperature of 7.5 eV, EIR 'switches on' as the upstream density is increased above a critical value of between 6 and 7×10^{19} m^{-3}. Further study shows that this threshold scales as $T_u \propto n_u^{0.51}$, consistent with an analysis of the heat conduction equation used in the model. This scaling is shown as a dashed line in Fig. 4 with points above the line predicted to be attached and points below the line predicted to be EIR dominated detached plasmas. Clearly the experimental results differ somewhat from the prediction but this is perhaps not surprising given the simplifications of the model. Nevertheless, the trend of detachment being obtained for higher upstream temperatures as the plasma density is raised is in general agreement with experiment.

5. Conclusions

Experiments on ULS have demonstrated the importance of both molecular activated and EIR processes in detached plasmas. EIR dominated plasmas are characterised by very low electron temperatures, with a significant population of non-equilibrium highly excited neutral hydrogen atoms. The threshold between EIR and MAR dominated detached plasmas has been studied in terms of upstream plasma parameters and are in reasonable agreement with simplified models of electron cooling and recombination processes: these models also reproduce the main features of the axial profiles of density and temperature in EIR dominated detached plasmas. As well as being of interest to other divertor simulators, these results are of significance to tokamak divertor plasmas, demonstrating that volume recombination involving MAR processes can be of importance in detached plasmas at higher upstream SOL temperatures than might be expected from purely EIR processes. Future work will concentrate on more realistic models of recombining plasmas with, for example, the explicit inclusion of MAR as well as studying the dynamic response of these detached plasmas to upstream heat and particle transients.

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