Plasma Recombination Regimes in the UMIST Linear System

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Introduction

The problem of power handling in proposed tokamak fusion reactors has been the subject of intense research within the fusion community and has led to a number of plasma divertor concepts, in which the region of plasma edge interaction is isolated from the main reactor chamber. One of these, the “gas target divertor”, where the exhaust plasma undergoes inelastic collisions with neutral atoms, offers the possibility of reducing the power loading on plasma facing materials in the divertor. Motivated by this, the study of atomic and molecular processes at the edge of fusion related devices has attracted increasing interest. In particular, studies on both tokamaks and so called “divertor simulators” have recently demonstrated the importance of recombination processes in the understanding of “detached” plasmas [e.g. 1,2] where the flux of ions to the divertor target plate is dramatically reduced. In this paper we present studies of recombination in a hydrogen plasma relevant to detached plasma operation in tokamak divertors. The UMIST Linear System (ULS) is a device designed to study a range of divertor physics issues and is capable of producing steady state plasmas with electron densities and temperatures in the range \(10^{17}-10^{19} \text{ m}^{-3}\) and 3-15eV respectively. Previous studies on the ULS have centred on the interaction between a hydrogen plasma beam and low pressure (<10mTorr) neutral hydrogen gas and have identified a regime in which molecular activated recombination (MAR) appears to be the dominant plasma loss process [3]. Here we report on further studies in which the upstream plasma parameters are varied such that three-body and radiative electron-ion recombination (EIR) can be made to dominate. We present detailed Langmuir probe and spectroscopic results of the resulting EIR dominated plasmas and investigate the parameters governing the threshold between MAR and EIR dominated regimes.

Characteristics of EIR dominated plasmas

Figure 1 shows a schematic diagram of the UMIST Linear System (ULS) showing the principal components of the device, and the location of the main diagnostic ports. The plasma source, based on a high output ion source described by Demikharnov et al [4], offers very high efficiencies (approaching 90% of the gas flow input), injecting a hydrogen plasma beam of approximately 1cm diameter at the typical field strengths of 0.1 Tesla in these studies. Approximately 45cm from the end plate of the ULS vacuum vessel is a diaphragm with an
aperture of 14mm diameter separating the upstream chamber from the “gas target” chamber. The gas introduced into the target chamber was hydrogen at a pressure of typically 8mTorr. Previous results from ULS have indicated that a strong reduction in plasma flux along the beam is observed with the introduction of gas into the target chamber. A detailed analysis of the possible origin of this reduction led to the conclusion that MAR processes play a significant role under these conditions and, within a factor of two, give quantitative agreement with the experimentally observed decrease in plasma flux [3]. By changing the plasma source conditions it is possible to establish a regime where electron-ion recombination becomes the dominant plasma loss process. In this case the reduction of plasma flux is more rapid, occurring over a scale length of approximately 10cm. Figure 2 illustrates this, showing axial profiles of $T_e$ and $n_e$ in the target chamber measured using a Langmuir probe introduced from the target plate end of the device. It can be seen that the electron density (calculated using classical assumptions of the flux of ions to a probe) falls dramatically in the region 18-25 cm from the target chamber diaphragm, coincident with the electron temperature decreasing to below 1eV. Experimentally, this region of density reduction is observed as a vivid, flame like blue glow. Spectroscopic studies of this region, utilising both high resolution visible and VUV spectrometers, indicate the presence of a very substantial population of highly excited neutral hydrogen atoms, characteristic of three body recombination processes. Figure 3 shows a typical spectrum from these recombining plasmas close to the hydrogen Balmer series continuum, with excited neutral atoms having principal quantum numbers up to $n=26$ clearly resolved. Furthermore, a detailed analysis of the Balmer continuum (resulting from radiative recombination) suggests a radial profile averaged electron temperature less than 0.1eV. All of these results are consistent with previous studies of divertor relevant plasmas dominated by electron ion recombination [5], and we conclude that the observed detachment for these plasmas can be explained by EIR processes.

**Dependence of recombination regime on upstream plasma parameters**

Having inferred the presence of both MAR and EIR dominated regimes in the ULS device, a detailed study of the dependence of the dominant mode of plasma recombination on upstream plasma parameters was undertaken. Experimentally it is found that the source output (in terms of upstream plasma temperature and density) is dependent on a number of external factors: for example, magnetic field strength, source gas flow, source arc current etc. In order fully to explore the operating space of the source, all of these factors were varied systematically over as large a range as possible so as to obtain a full operating space diagram for the source. With
a gas target pressure of 8mtoorr, it was found that for all of the conditions obtained the plasma was detached, or partially detached, from the end target plate. Spectroscopic monitoring of the plasma in the gas target chamber was used to determine the mode of recombination. The results are shown in Figure 4; notice there is quite a distinctive boundary between the regions of parameter space in which the two modes of recombination are obtained. A simplified analysis by Krasheninnikov et al [6] suggests that the dominance of EIR processes over MAR is the result of competing effects of recombination and electron ion-cooling. We thus find a simple analytical expression for the threshold between the EIR and MAR of the form

\[ T_e = C n_e^{2/3} \]

\( C \) is a constant derived from parameterisations of the relevant rate constants). This is also shown on Figure 4; the agreement is reasonable but clearly a more detailed analysis is required for fuller understanding.

To model the plasma profiles, we are using the simple 1D theory [6] including electron cooling due to collisions with cold ions and a diffusive plasma flux with particle loss by recombination. These assumptions (cool ions; neglect of ionisation, radiation; neglect of convective terms in the momentum balance) will subsequently be relaxed, as they are not fully appropriate for the ULS conditions but the model provides a first step to predicting a transition between EIR and MAR dependent on upstream conditions and to explaining the observed profiles (e.g. Figure 2). We solve the fourth order set of equations

\[
\frac{d}{dx}\left(\kappa_e \frac{dT_e}{dx}\right) = \left(\frac{3}{2}\right)\nu n_e(T_e - T_N) \quad \frac{d}{dx}\left(\frac{1}{MV_{in}} \frac{dp}{dx}\right) = (v_{EIR} + v_{MAR})n_e, \quad (2)
\]

initially neglecting MAR and assuming \( T_n = 0 \), using a Runge-Kutta algorithm, with sheath boundary conditions at the end plate. Preliminary results suggest that for upstream temperatures and densities typical of the ULS, the cooling predicted within this model is rather too weak for the onset of EIR, but further investigation is required.

**Conclusions**

Experiments on the UMIST Linear System have demonstrated the importance of recombination processes in the understanding of hydrogen plasma-neutral gas interactions of relevance to tokamak divertors. Both molecular activated and electron ion (radiative and three body) recombination dominated regimes have been identified. EIR dominated plasmas have been shown to result in characteristically very low temperature plasmas, 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 found to be in reasonable agreement with simplified models of electron cooling and recombination processes. Future work will be directed at developing more complete numerical models of recombining plasmas to compare with experimental results.

Acknowledgements B Mihaljcic gratefully acknowledges studentship support from EPSRC.

References


![Figure 1 Schematic of ULS](image1)

**Figure 1** Schematic of ULS

![Figure 2 Axial profiles of electron temperature (dotted curve) and density (solid curve) in the EIR regime](image2)

**Figure 2** Axial profiles of electron temperature (dotted curve) and density (solid curve) in the EIR regime

![Figure 3 Spectrum of recombining plasma showing Balmer series lines and continuum](image3)

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![Figure 4 Upstream conditions for obtaining MAR (open points) and EIR (solid points); the curve is the fit $T_u = Cn_u^{2/3}$](image4)

**Figure 4** Upstream conditions for obtaining MAR (open points) and EIR (solid points); the curve is the fit $T_u = Cn_u^{2/3}$