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Spatial structure of detached plasmas in the ULS divertor simulator

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Abstract

The UMIST Linear system (ULS) is a linear plasma device designed to study plasma and atomic physics issues relevant to tokamak divertors. The ULS produces a steady state plasma beam which interacts with neutral gas in a target chamber. Dependent on the upstream conditions, either electron-ion recombination (EIR) or molecular activated recombination (MAR) may dominate. Here we report on detailed studies of the plasma spatial structure in both regimes. A specially designed optical spectroscopy probe is used to measure the visible emission, with spatial resolution less than 5mm. Atomic and molecular lines are identified, and the results are interpreted using a collisional-radiative model, enabling the MAR rate to be calculated. One dimensional plasma modelling also demonstrates a transition between EIR and MAR dominated regimes, as the upstream conditions are varied.

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1. Introduction

In order to minimise plasma surface interactions in devices such as ITER, considerable attention has focused on the detached regime of operation, in which there is a dramatic drop in particle and heat fluxes to divertor target plates. This regime is characterised by low temperatures and strong pressure gradients parallel to the magnetic field, and studies in both tokamak divertors and linear simulators show that it is associated with volume recombination processes. Both direct electron ion recombination (three body and radiative), EIR, and, as has been the subject of many recent studies, molecular activated recombination, MAR, may play a role [1–3]. The latter process requires the presence of vibrationally excited hydrogen (or other) molecules and proceeds either through dissociative electron capture followed by mutual neutralisation of negative and plasma ions, or by ion conversion between molecules and plasma ions followed by dissociative recombination of molecular ions.

The UMIST Linear System (ULS), described in more detail in [4,5], is a linear plasma device designed to study a range of edge physics issues relevant to tokamak gas target divertors, at present focusing on the role of recombination in detached plasmas. It produces steady-state plasmas with electron temperature 2–15eV and a wide density range, $10^{17}–10^{19}\,\mathrm{m}^{-3}$; these upstream conditions may be reliably controlled by varying the

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source parameters. The plasma flows into a gas target chamber, separated from the upstream chamber by a plate with an orifice. Previous studies [4–6] have focused on the interaction of hydrogen plasma with hydrogen gas. It has been shown that, at lower upstream densities, a detached regime is attained for gas target pressures above about 2 m torr, and it has been inferred that MAR dominates the plasma loss; by increasing the upstream density, EIR can be made to dominate. The threshold for transition to EIR (occurring at high densities/low temperatures) has been determined [6].

Previous work, however, has not directly demonstrated the presence of MAR in the ULS. Nor has it been clear whether there is a complete transition between regimes, or whether MAR persists even in the EIR dominated regime. Here we begin to tackle these questions, as well as to study in more detail the underlying processes. The focus of this paper is the interpretation of spatially resolved spectroscopic and Langmuir probe data, supported by a 1D plasma model and collisional-radiative modelling.

2. Probe studies and spatially resolved spectroscopy

Extensive measurements of both the radial and axial structure of the plasma in the target chamber have been undertaken using Langmuir probes [4–6]. The first studies of recombining plasmas in the ULS [4], in the lower upstream density conditions, demonstrated that the radial profiles were almost constant along the beam, and there was no evidence of radial broadening of the profiles. From this it was inferred that radial diffusion was insignificant, and hence some volumetric plasma particle loss mechanism was required, presumed in these conditions to be MAR. However, recent results from other linear devices have suggested that net radial transport may occur through transient fluctuations [7]: these have been interpreted as outwardly moving plasma 'blobs'. ULS probe measurements reported previously used a data acquisition system whose bandwidth was limited to <5 kHz, so it is possible that, when higher frequency fluctuations are accounted for, the profiles are broader. However, recent measurements with a fast probe (bandwidth up to 2 MHz) show that this is not the case: the radial profiles are no broader for the fast probe. Hence we conclude that, for the conditions reported here, there is no evidence of significant radial transport in the ULS due to fluctuations. Thus, we continue to propose that the particle balance is predominantly axial.

Langmuir probes measurements are difficult to interpret in low temperature recombining plasmas, and must be complemented by spectroscopy. Many previous studies on divertor simulators access only one spatial location and vary the neutral gas pressure in order to investigate the transition to recombining regimes, and thus provide no information about spatial structure. To this end, we have designed and built a new optical spectrometry probe, using a moveable system of collection optics inserted into the target chamber outside the plasma beam. At present, we take a series of lines of sight across the beam centre, at axial positions at 5 mm intervals from orifice to target (radial profiles will be measured in future), for typical MAR and EIR dominated cases.

Spectroscopically, the EIR dominant regime is characterised, as expected, by a sharp rise in the relative strength of the higher n Balmer lines (especially $n = 4, 5$), in the region where probe measurements indicate low temperatures and a sharp drop in plasma flux (Fig. 1). The distinction between the two regimes is highlighted by the ratio of Hα to Hγ emission, which falls sharply in the recombination zone in the EIR case, but is fairly uniform in the MAR case (Fig. 2(a). In the conditions where it is supposed MAR is dominant, strong lines of the Fulcher molecular spectrum are seen, with intensity decreasing along the beam (Fig. 2(b). This indicates a significant population of vibrationally excited hydrogen molecules, which, dependent on the distribution between levels, is a requirement for MAR. Interestingly, a region in which the Fulcher band is quite strong is also found upstream of the EIR recombination region in the EIR case (Fig. 2(b). This suggests that, at the higher densities and temperature in this upstream region, there is some MAR, but as the temperature falls, EIR begins to dominate particle losses.

Temperatures in the EIR recombining region, where there are strong high n Balmer lines, can be inferred from this data using Boltzmann plots. This gives a temperature falling slightly through this region from about

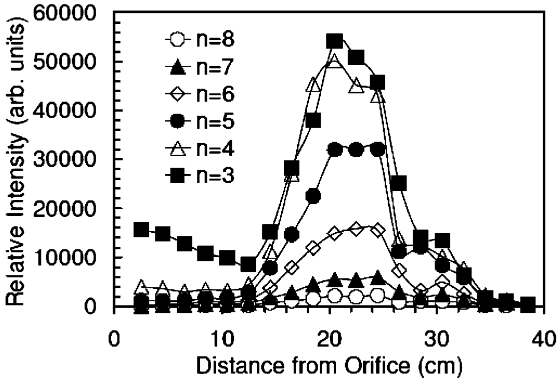

Fig. 1. Balmer line intensities ($n = 3$–8) as a function of axial distance in the gas target chamber (EIR case); higher n lines up to about $n = 20$ are also detected in the recombination zone. The EIR dominated region (blue glow) begins at about 15 cm; upstream of this, MAR predominates.

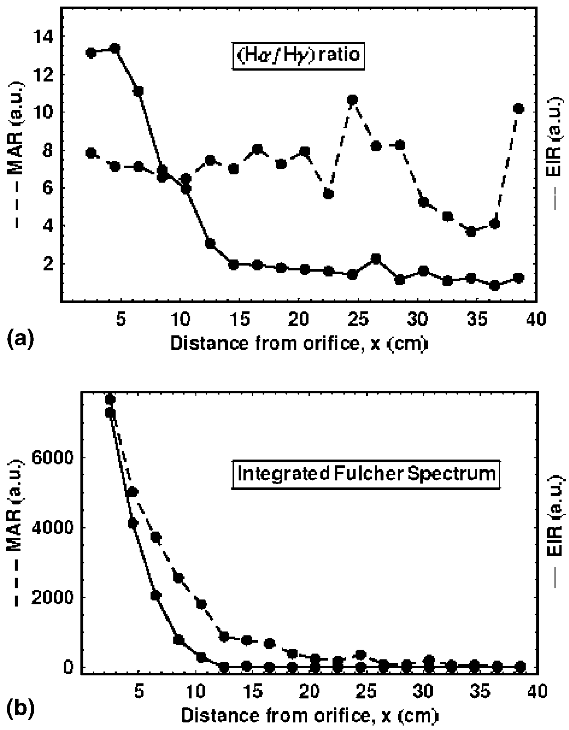

Fig. 2. (a) The ratio of Hα to Hγ line intensities and (b) the total intensity of the Fulcher band, as a function of axial distance in the target chamber, for typical EIR and MAR dominated plasmas.

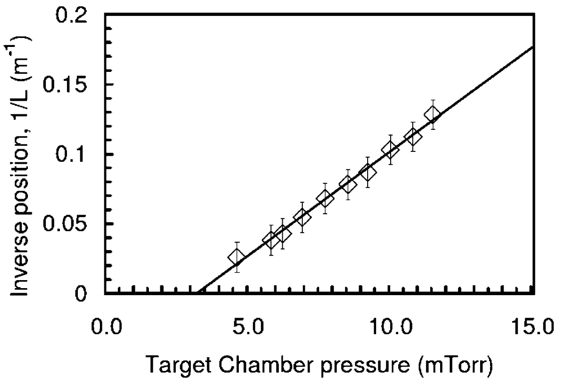

Fig. 3. The inverse (1/L) of the distance (L) of the Hα minimum from the orifice, as a function of neutral gas pressure (P) in the target chamber.

0.13 ± 0.02eV at 18.5cm to about 0.08 ± 0.02eV at 32.5cm from the orifice; but it should be noted that this is line-averaged information across beam radius and is weighted to locations with maximally excited atoms. This temperature, which is too low to be resolved by the present probe measurements, is consistent with that expected for EIR (and found in the modelling, described below).

A minimum in the Hα emission is a signature of a transition between regions dominated by ionisation and recombination. Such a minimum is clearly found in the EIR dominated plasmas, as may be seen in Fig. 1 at about 12cm, which is just upstream of the observed blue glow. The position of this boundary changes with the neutral gas pressure, such that the inverse scale length varies linearly with the gas pressure (Fig. 3). This suggests a simple linear scaling of the scale length with ion-neutral collision frequency, and hence, upstream of the recombination zone, the ions slow down and cool through collisions with the neutral gas. Clear evidence for charge-exchange collisions is provided by preliminary studies of a hydrogen plasma beam entering a deuterium gas chamber; in this case, the high n Balmer lines in the recombination region are observed to originate from Deuterium atoms. Since this radiation arises directly from recombined ions, this shows that the plasma ions are D^+, demonstrating the importance of upstream charge exchange in EIR dominated plasmas.

Using a 0D Collisional Radiative model [8,9], it is deduced from local spectra that the degree of dissociation of molecular hydrogen to atoms is 4%, from which we may estimate the ion-neutral collision frequency (ν_{in}), accounting both for molecular collisions (elastic), dominant at ion energies below about 5eV, and atomic collisions (charge exchange), dominant for the higher energies which are more relevant for the upstream ions in the ULS. It is found that the total ν_{in} depends only weakly on energy, and is around 2MHz for the standard gas pressure of 10mTorr. Furthermore, MAR rate coefficients are determined for a range of plasma parameters, which, consistent with previous work [1], depend quite weakly on density in the relevant range and have a broad maximum of around $2 \times 10^{10}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $T_e \approx 1$–2eV. Both these parameters are required in the plasma modelling below. Using probe measurements for the MAR case, we estimate the diffusive plasma flux $\Gamma = (1/\nu_{\mathrm{in}})(-\mathrm{d}P/\mathrm{d}x)$. From the MAR rate coefficients, we thus find the length scale for flux reduction due to MAR to be about 2cm.

3. Modelling of plasma profiles

In order to model the underlying physics of the transition between EIR and MAR, we use a simple 1D (axial) model incorporating electron energy balance, with cooling due to collisions with cold ions (equilibrated with the neutral gas whose temperature $T_N \approx 0$), and particle balance, with sources/sinks due to both modes of recombination and ionisation [1]. We thus solve numerically

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(\kappa_\mathrm{e}\frac{\mathrm{d}T_\mathrm{e}}{\mathrm{d}x}\right) = \left(\frac{3}{2}\right)\nu n_\mathrm{e}T_\mathrm{e},$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{1}{M\nu_{\mathrm{iN}}}\frac{\mathrm{d}p}{\mathrm{d}x}\right) = (\nu_{\mathrm{EIR}} + \nu_{\mathrm{MAR}} - \nu_{\mathrm{ion}})n_\mathrm{e}, \qquad (1)$$

where the MAR rate coefficient (ν_{MAR} as a function of T_e and n_e is taken from the collisional radiative model. Sheath conditions are specified at the target plate, whilst the upstream orifice temperature and density, T_o and n_o are prescribed (in practice, the equations are integrated downstream from the target plates, with iteration to achieve the upstream boundary conditions).

Initially, ionisation is neglected. For the range of parameters considered, MAR is always significant, and (when EIR is negligible), there is a drop in plasma flux due to MAR indicative of a detached regime. At fixed orifice temperature, T_o, there is an almost discrete transition to EIR as the orifice density is increased, consistent with previous results (neglecting MAR) which exhibited a sharp onset for EIR [6]. Typical profiles are shown in Fig. 4, for the same upstream temperature but different densities. For low upstream density, the profile (Fig. 4(a) is detached, which can be confirmed by a drop in the plasma flux, with plasma loss due almost entirely to MAR. In the high density case, whilst there is still a MAR region upstream in which the plasma flux drops steadily, there is also a distinct EIR region downstream, which may be seen in Fig. 4(b) as the region of very low temperature ($T \approx 0.1$ eV). The detachment is much deeper in the EIR case, with the plasma flux dropping by many orders of magnitude more than the MAR-only case.

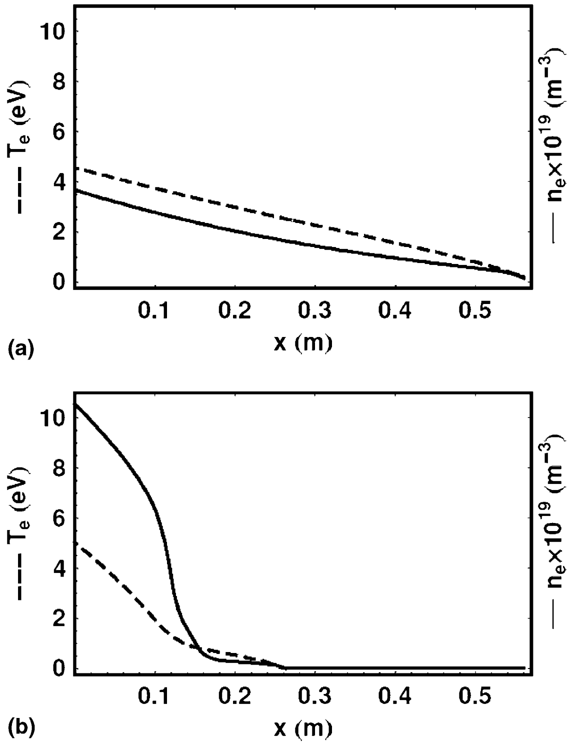

Fig. 4. Modelled axial profiles of temperature and density, for the same upstream temperature but different upstream densities, typifying (a) the MAR case and (b) the EIR case. In (b), the region in which the EIR particle sink term dominates over MAR is from about 25 cm to the target plate.

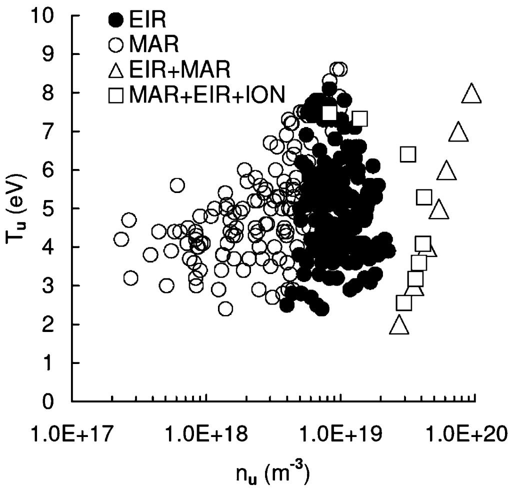

Fig. 5. The conditions for the onset of EIR in terms of the upstream density and temperature (n_u and T_u) showing experimental points (white – MAR dominated; black – EIR dominated) and the modelled threshold (triangles – including MAR and EIR; squares – including MAR, EIR and ionisation).

By varying the upstream conditions and monitoring the onset of EIR, a threshold for transition between the two recombination regimes can be predicted. This is shown in Fig. 5, together with experimental measurements of the threshold. Note that the shape of the theoretical threshold curve is similar to observations, but the modelled profiles require higher densities for transition to EIR. At this stage we incorporate the effects of ionisation in the model. This is strong upstream for the higher orifice temperatures, and has the effect of causing an initial rise in the density, as is indeed observed in the Langmuir probe measurements [4,5]. Thus, when ionisation is included, the onset of EIR is facilitated. This shifts the threshold curve somewhat to the left in n_u, T_u space, as seen in Fig. 5.

4. Conclusions

Detailed information about the spatial structure of detached recombining plasmas in the ULS has been obtained spectroscopically. For lower upstream densities (higher upstream temperatures), the plasma flux is reduced through MAR. We have shown that the scale lengths for MAR are sufficiently short that MAR can indeed account for the plasma loss. At higher upstream densities, a MAR region persists, but there is also a EIR dominated region downstream, characterised by very low temperatures and strong emission in high n Balmer lines. We interpret the results, using a 1D plasma model, as follows. When the plasma enters the gas target chamber, the ions are slowed down and cooled by collisions with the neutral gas, both charge exchange and elastic scattering. We estimate the distance L_{ion} over which ions are slowed down from $v\,\mathrm{d}v/\mathrm{d}x \approx -v_{\mathrm{in}}v$, where v is the ion speed, giving $L_{\mathrm{ion}} \approx v/v_{\mathrm{in}} \approx 4\,\mathrm{cm}$ for ions with initial energy 50 eV (the ULS plasma source produces such high energy ions [4]). The electrons then cool by collisions with the cold ions and, if the density is sufficiently high, there is a sharp transition to an EIR dominated regime in which the plasma flux drops much more strongly. Interesting evidence of charge exchange has been provided by preliminary mixed gas studies, which will be extended in future.

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