A study of impurity transport in the plasma boundary of TEXTOR using gas puffing

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The transport of carbon and oxygen impurities has been studied in TEXTOR by introducing the gases CH₄ and CO through a small hole in a test limiter. The toroidal distributions of different charge states of the impurities have been measured using a CCD camera with optical filters. Local impurity ion temperatures have been calculated from the Doppler broadening of line emission measured with a high resolution spectrometer. The spatial distributions and the ion temperatures have been modelled using the LIM Monte Carlo impurity code, with experimentally measured plasma profiles. Good agreement is obtained for both sets of measurements. The comparison shows the breakup energies of the atomic fragments to be ≤ 1 eV. The fuelling efficiency of different gas species is discussed.

1. Introduction

Impurity transport in the boundary layer of tokamaks is a relatively neglected topic both experimentally and theoretically. Nevertheless, it could be crucial in determining the effective impurity concentrations and hence the thermonuclear power output of tokamaks. The problem is that impurities frequently come from localised sources, e.g. limiters and divertor targets and that these sources are also sinks. Impurity atoms released from a surface enter the plasma and are rapidly ionized and heated and at the same time undergo transport along and across the magnetic field. If ionization occurs within the scrape-off layer (SOL), the impurity ions are subjected to frictional forces due to plasma ions streaming along the field to the limiter and to electric forces due to the presheath field. As a result of these processes there is a finite chance that impurity ions will return promptly to the limiter before contributing significantly to the dilution of, or radiation from, the bulk plasma. Because of the localised sources and sinks the problem is inherently 3-dimensional and hence difficult to analyse. A 3D Monte Carlo code has been developed [1] and compared with a limited set of experimental data [2–5]. In the present study we have extended these measurements using a system of gas puffing through a test limiter to introduce impurities into the plasma boundary of TEXTOR. Detailed measurements of the transport of low charge state impurities along the field lines have been made using a high resolution spectrometer and used to study the heating process.

2. Experiment

Typical operating conditions of the TEXTOR tokamak [6] for the present series of experiments are \( I_p = 340 \) kA, \( B_T = 2.0–2.28 \) T, \( n_e = (2–3) \times 10^{19} \) m⁻³, \( T_{e0} = 1.2 \) keV. In a small number of discharges neutral beam heating was added using one or two beam lines (≤ 4 MW). Fig. 1 shows the geometry of the graphite test limiter arrangement, the gas puff system and spectroscopic diagnostics. For these experiments the ALT II belt limiter and the poloidal rail limiters were at a minor radius of 46 cm. The radial position of the test limiter could be varied between 45 and 50 cm. Impurity gases were injected from a gas handling system through
Fig. 1. Schematic of the TEXTOR test limiter showing CCD camera and high resolution spectrometer viewing positions and gas injection system.

A tube to the tip of the limiter. The gas puff time could be varied but was usually set at 0.6 s when the plasma current and density had reached constant values. The two main impurity gases injected were carbon monoxide and methane, with a typical gas pulse duration of 1 s. Feedback control of the plasma density ensured no density rise occurred as a result of the puffing. Measurements of the reduction in the deuterium gas feed rate showed that the fuelling efficiency of these injected impurities was in fact very low, typically < 0.1 electrons/molecule, consistent with previous observations on TEXTOR [7] and other tokamaks [8,9]. Two optical viewing systems looking at the test limiter from ports on the top of the vessel allow both the toroidal and poloidal distribution of the radiation to be observed. The CCD camera provided a 2D picture, recorded on tape and digitized after the discharge. Optical interference filters for the lines CI (909.5 nm), CII (657.8 nm), CII (426.7 nm), OI (844.6 nm), OII (441.5 nm) and Ha (656.3 nm) were used. Filters were changed between successive discharges. The test limiter was also observed with a high resolution visible spectrometer capable of both wavelength and spatial spans. The wavelength scan range is ~1 nm, achieved by rotating a glass plate in the optical path inside the spectrometer. Toroidal spatial scans over a range of ±10 cm are obtained by an oscillating external mirror. A number of different lines were studied eg CII (657.8 nm), CIII (464.7 nm) and OII (464.9 nm). The instrumental line width of the spectrometer was determined at different wavelengths using low pressure discharge lamps and the dispersion measured at selected wavelengths using well known doublet lines. Typical resolution was 0.01 nm. A polarizer was used to reduce the effect of Zeeman splitting. Impurity ion temperatures were derived from the Doppler broadened line shapes by a non-linear least squares fit to modelled line shapes constructed from the convolution of the measured instrument profile with Gaussian intensity distributions calculated from the spectroscopic term configurations. Excellent fits were usually obtained with uncertainties in the temperature of the order of 10%. In order to calculate the rates of heating and ionization for comparison with the theoretical model, the local plasma density and temperature

Fig. 2. Temperature and density profiles in the TEXTOR boundary measured by lithium beams [10], langmuir probes and Li/C laser ablation pulsed system [10].
conditions must be measured. For the present experiments, we have made use of a number of the TEXTOR edge diagnostics. The edge density and temperature profiles were measured using a continuous lithium atomic beam from an oven [10], a pulsed lithium/carbon beam from laser ablation [10] and with a reciprocating langmuir probe. Typical examples of the density and temperature profiles are shown in figs. 2a and 2b.

3. Results

3.1. Spatial distributions

With the test limiter at 46 cm, the spatial distributions of the charge states of CI, CII, CIII, OI and OII resulting from CO puffing, have been studied. Results are shown in fig. 3 for the carbon states. As has been observed in earlier studies [5] the neutral carbon is well confined to the source region consistent with a low ionization mean-free-path $\lambda_i$. The CII is significantly broader, due to the ions streaming along the field after ionization. However, the ionization rate of CII is high, resulting in relatively rapid transfer to CIII. The spatial distribution of the CIII (measured with the spectrometer) is much broader. This is due to its higher temperature and the somewhat lower ionization rate to CIV. Results for OI and OII are shown in fig. 4. The spatial distribution of OI is practically identical to that of CI, but the OII distribution is somewhat narrower than for CII. The carbon distributions during methane puffing have also been studied. As expected no significant increase in emission of oxygen light over background was observed. The CI and CII distributions are identical within experimental error to those obtained for CO puffing. This indicates that the dissociative kinetic energies of the carbon atom are similar for the two molecules. In addition to the spatial distributions of the impurity species introduced by gas puffing, measurable signals are obtained for some lines from the intrinsic impurities produced by erosion processes at the test limiter. The distributions are markedly different from the gas puff results, reflecting the different spatial distribution of the source. In common with earlier results from DITE [11] and JET [12] there is a minimum in the centre of the limiter, where field lines are tangential to the surface, and two maxima on either side. The spatial distributions of the individual charge states vary significantly as the position of the gas puff is changed in minor radius. At large radii, far from the last closed flux surface, the plasma density and temperature are low, \( (\approx 10^{17} \text{ m}^{-3}, 10 \text{ eV}) \) neutral carbon atoms have longer mean free paths resulting in a broader CI distribution. As a consequence, the CII source function is broader and the CII can travel further before ionisation to CIII.

3.2. Impurity ion temperature

Using the high resolution spectrometer, we have looked at the doppler broadening of OII, CII and CIII ions under a range of experimental conditions, simultaneously with the observation of the spatial distributions.
Fig. 5. Comparison of experimental line shapes of O\textsc{II} (a) and C\textsc{III} (b) for CO puffing with model including instrumental width, Zeeman splitting and finite ion temperature.

described in section 3.1. A typical line profile of C\textsc{III} ($\pi$ polarisation) is shown in fig. 5 together with the theoretical line shape, calculated as discussed in section 2. Experimental line shapes corresponding to Zeeman $\sigma$ polarisation are more complex and were observed during only 2 or 3 discharges. Within the experimental errors, they gave temperatures in agreement with $\pi$ observations. The temperature of CII is found to be significantly lower than that of C\textsc{III} under identical plasma edge conditions. Typical temperatures for the line of sight of the spectrometer viewing the limiter tip are $3.0 \pm 1.0$ eV for CII and $10 \pm 2$ eV for C\textsc{III}. The ion temperature is observed to vary with spatial position toroidally, increasing with distance from the source as shown in fig. 6 for O\textsc{II} and C\textsc{III}. Variation of the ion temperature with the position of the test limiter and with the gas puffing rate have also been investigated [13]. Changing the test limiter radius varies the local density and temperature of the plasma into which the molecules are injected and therefore the relative importance of ionization and heating. As the gas source is moved radially inward the C\textsc{III} temperature increases, presumably because the ionization time decreases faster than the heating rate. Ion temperatures have also been measured for different gas puff rates. In general, the ion temperature increases as the gas puff decreases, the effect being more marked for the higher ionisation states. This is evidence that the gas puffing is disturbing the local plasma, possibly lowering the local electron and/or ion temperature. Most of the data, including all the spatial distributions presented in section 3.1, have been measured using the lowest gas puffing rate compatible with reasonable diagnostic signals, typically 0.3 mb l$s^{-1}$.

3.3. Fuelling efficiency

To date, only preliminary measurements have been made of the global effects of impurity injection. Simple measurements of the decrease in deuterium gas fuelling rate give a measure of the additional electrons introduced into the plasma by a given molecular flux of impurities. We define the fuelling efficiency as the number of additional electrons per gas molecule introduced. Experimentally, we find this figure to be $\leq 0.1$ electron/molecule for both CH$_4$ and CO whereas for H$_2$ and He it is of the order of unity. The large difference cannot be easily explained by different recycling properties since the hydrogen in CH$_4$ and oxygen in CO are both recycling species. Further experiments are planned to see if the gas efficiency behaviour can be predicted by the modelling and correlated with any of the other experimental measurements.

4. Modelling with the LIM Monte Carlo code

LIM is a 2D/3D Monte Carlo code developed to interpret edge impurity experiments [1]. Experimental profiles of density and temperature of the background plasma are used as input to the code together with the limiter shape, plasma minor radius and SOL connection length. Impurities are launched with a predetermined energy distribution. Each neutral is followed in 2D or 3D space until ionization. The ion is then followed in its parallel (assumed classical) and cross field diffusion (assumed anomalous with specified $D_\parallel$ and $V_{\text{pinch}}$), with further ionisation and/or recombination and thermalisation with the background ions according to Spitzer times, until it reaches the wall or returns to the limiter. The code output gives the temporal evolution of the spatial distribution of each charge state cloud, after instantaneous injection. Steady state fluxes are modelled by time integration. For purposes of comparison with spectroscopic observations the code calculates the spatial distribution of line emissions from specific transitions of interest. From the literature it is clear that the dominant reaction for CO molecules at the electron
temperatures of interest is the formation of the molecular ion CO$^+$ [14]. This ion is then dissociated through two channels to form C$^+$ + O or O$^+$ + C [15]. The energy of the dissociation products of the neutral molecule is typically $\sim 0.05$ eV [16] and it has been postulated that the breakup of the molecular ion will lead to similar energies [15]. The source position and energy has been estimated under this assumption and the densities of the different charges states calculated. From these and the appropriate photon efficiencies [17] the chord integrated line intensities for the experimental geometries are evaluated. The results are shown for the carbon ions in fig. 3 and the oxygen ions in fig. 4 are in good agreement with the experimental data. Impurity ion temperatures have also been calculated using the same input parameters. It is found that the ion temperature increases with charge state. This is due to heating by collisions with plasma ions before ionisation to the next charge state [13]. The calculated impurity ion temperatures are compared with the experimental data in table 1, for ions located close to the source. The toroidal variation of ion temperature away from the source has also been modelled and is compared with the data in fig. 6. The calculated value of $T_i$ depends quite strongly on $Z_{\text{eff}}$, due to the increase in collision rate with $Z$. The agreement is remarkably good for the CIII ions assuming $Z_{\text{eff}} = 1$. For the OII ions the modelled values of $T_i$ are about a factor of 2 lower than the experimental ones for $Z_{\text{eff}} = 1$.

**5. Discussion**

The experimental spatial distributions are consistent with the LIM modelling only for the low energies ($\sim 0.05$ eV) expected from the atomic physics data [15,16]. This is in contrast with our previous modelling which deduced an initial atom energy of $\sim 1$ eV from radial profiles of carbon and oxygen during CO puffing [5]. At that stage we were unaware of the recent atomic physics data and had assumed that dissociation occurred before ionisation. The earlier radial profiles will be reanalysed using the lower dissociation energy. The fact that the CI, CII and CIII spatial distributions from CH$_4$ injection are the same as the distributions from CO, within experimental error, implies that the energies of the atoms resulting from the dissociation of CH$_4$ are also very low. The measured ion temperatures show clearly that the impurity ions take a finite time to heat up to the background plasma temperature. This is in qualitative agreement with simple analytical modelling [13]. This result is important because it can affect the transport near the source and hence the probability of impurities returning promptly to the limiter. Fluid codes which typically assume that the impurities instantly thermalise with the background do not model this aspect.

| Table 1 | Calculated impurity ion temperatures compared with the experimental data |
|-----------------|-----------------|-----------------|-----------------|
|                | Impurity ion temperatures |
|                | OII  | CII  | CIII |
| LIM ($Z_{\text{eff}} = 1$) | 1    | 1    | 5    |
| ($Z_{\text{eff}} = 3$)    | 3    | 2.7  | 11   |
| Experiment       | $3.0 \pm 0.5$  | $3.0 \pm 1$    | $10 \pm 2$     |

Fig. 6. Toroidal variation of OII and CIII ion temperatures during CO puffing experiment. Continuous lines are predictions from LIM model for $Z_{\text{eff}} = 1$ and $Z_{\text{eff}} = 3$. 
of impurity transport. The constraints put on the model in having to predict the spatial distribution of the different charge states and their temperatures are quite severe. The good general agreement between experiment and theory lead us to believe that we have a good physical description of all the important physical processes. The most important question now is whether we understand impurity transport sufficiently well that we can determine the conditions under which contamination of the plasma is minimized. Our results on fuelling efficiency measurements confirm earlier investigations [7] that some gases, e.g. CO and CH₄ have a very low gas efficiency, \( \leq 0.1 \) electrons/molecule, whereas in other gases e.g. H₂, D₂, He, the efficiency is close to unity. The situation is complicated by whether the injected gas is recycling or non recycling.

6. Conclusion

The spatial distributions and the temperatures of different charge states of impurities introduced as gaseous species at the last closed flux surface have been studied. The results are in good agreement with the LIM code for impurity transport. The behaviour of carbon from CH₄ and CO is very similar and we conclude that in both cases the dissociated carbon atom has close to thermal energy. The temperature of the impurity ions is observed to increase as they move away from the source and increase in charge state. In general, it is important to include this heating rate in any transport modelling. The assumption of instantaneous heating in models is not justified and can give erroneous results. Preliminary measurements indicate that the probability of the impurities studied entering the plasma is much lower than that of a hydrogen or helium introduced at the same location in a similar discharge i.e the effective screening of these impurity species is high. This screening is obviously very advantageous and the future impurity transport programme will concentrate on a better understanding of this process and finding ways of optimizing it.

References