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STUDIES OF HEATING AND IMPURITY TRANSPORT IN THE PLASMA BOUNDARY OF TOKAMAKS

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1. INTRODUCTION

Impurities in fusion plasmas lead to a loss of reactivity by radiation and fuel dilution.[1] The impurity concentration in the plasma is determined both by the production rate and transport in the plasma, particularly the transport in the boundary layer.[1,2] In this layer impurities, usually starting as cold atoms or molecules, are ionised and heated while diffusing both parallel and perpendicularly to the confining magnetic field. Atomic physics plays an important role in these processes. In the present paper we consider some of the experimental results on impurity behaviour in this boundary and some simple models to describe their behaviour. The discussion will be on the behaviour of impurities in plasmas bounded by limiters.

2. FUELLING OF IMPURITIES; He, Ne and Ar

Impurities entering as neutral atoms have an ionisation mean free path determined by the local electron density $n_e(r)$ and temperature $T_e(r)$. For an atom with a velocity v_o in the radial direction, the local ionisation rate is:

$$S(r) = \frac{d}{dr}\,[F_o\ exp\ \{-\int n_e(r)\ \overline{\sigma v}(r)/v_o dr\}] \tag{1}$$

where $\overline{\sigma v}$ is the ionisation rate coefficient for a maxwellian distribution, and F_o is the initial flux. From measured $n_e(r)$ and $T_e(r)$ profiles an estimate can be made of the impurity source function S(r). In the case of molecules the situation is more complicated because molecular ionisation frequently occurs first, followed by parallel transport, dissociation and further ionisation.

Impurity injection experiments are a valuable method of studying impurity transport. Injection of rare gases into the TEXTOR tokamak has shown that the impurity concentration in the edge builds up linearly at short times and tends to a steady state value at times long compared with the effective particle replacement time τ_p^*.[3] The edge impurity concentration N can be described empirically by an expression applicable to a zero dimensional model

$$N(t) = S_o\tau_p^* + (N_o - S_o\tau_p^*)\ exp\ (-t/\tau_p^*) \tag{2}$$

where N_o is the initial concentration and S_o is the total influx across the last closed flux surface (LCFS). The real particle replacement time is given

by $\tau_p = \tau_p^*$(1-R) where R is the recycling coefficient of the impurities at the limiter.

Experiments have been carried out introducing He, Ne and Ar to determine the effective fuelling rates. The time dependence of the plasma parameters during neon injection is shown in fig. 1. The rate of gas injection is constant for a period of 0.5 sec during the plasma pulse. The electron density is also maintained constant by a feedback system controlling the main gas species. The radiation from the neon, NeIII, increases almost linearly during the injection period and the total radiation and the central effective charge, Z_{eff}, increase correspondingly. When the impurity gas inflow is switched off the signals characteristic of the impurity decay exponentially with time during the period when the background density and plasma current remain constant. This behaviour is predicted by the simple 0-D model described above. There is the possibility that the time constants are largely determined by impurity transport in the plasma rather than by τ_p^*. However, independent experiments [4], using very short (20ms) He injection bursts, have shown that the measured time constant for transport to the centre was $\leq$ 100ms. Similar results have been obtained in TFTR.[5] The time constants observed in the present experiments for He, Ne and Ar are much longer than those obtained for transport in the plasma and this indicates that they must be determined by τ_p^* which in turn implies high recycling coefficients.

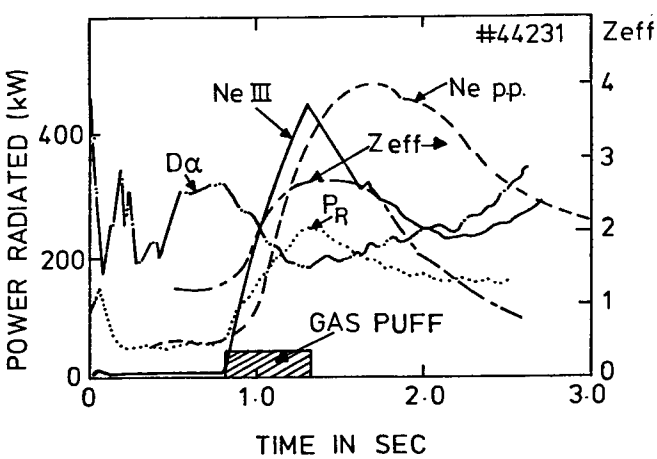

Figure 1: *Time dependence of $P_R, Z_{eff}, NeIII, D_\alpha$ and neon partial pressure during a 0.5s neon gas puff at the plasma wall in TEXTOR. $I_p^3 = 350kA$, $\overline{n}_e = 2 \times 10^{19} m^{-3}$.*

Measurements for a series of different gas puffing rates have been carried out for He, Ne and Ar. By measuring Z_{eff} and calculating the number of impurity atoms in the plasma (assuming Z_{eff} is constant across the plasma), we can obtain the ratio of the number of atoms in the plasma to the total number injected. This is a measure of the fuelling rate. Results from such experiments in TEXTOR show that while helium has a high fuelling rate, $\sim$ 100%, neon has a lower value, 40%, and argon is lower still, $\sim$ 3%.

The ionisation rate has been calculated as a function of radius for the three gases using equation 1 and the directly measured density and temperature profiles. The results are shown in fig. 2. It is clear that for a source at the

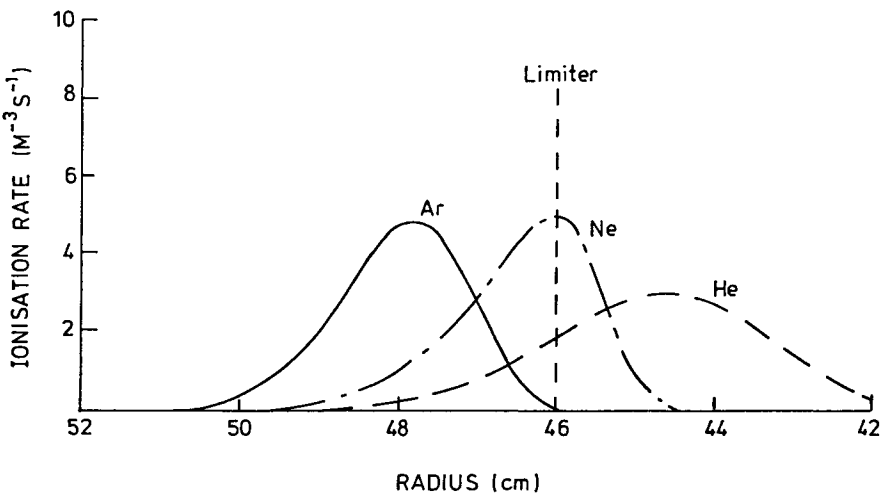

Figure 2: *Calculated ionisation rate of 0.05eV atoms starting from the wall (r = 52cm) using measured $n_e(r)$, $T_e(r)$ profiles for He, Ne and Ar.*

wall, the argon is ionised further out radially than the neon. The helium atoms are mostly ionised radially inside the last closed flux surface. The ionisation of the argon outside the LCFS is not, however, a complete explanation of the low impurity content in the plasma, since argon ionised outside the LCFS will in general hit the surface of the wall or limiter and recycle. By a series of such collisions it could eventually "walk" in to the LCFS. However, experiments comparing operation with the ALT II pumped limiter [6] on and off, has given direct evidence that argon is trapped in these surfaces more than neon or helium, fig. 3. Whereas when the pumped limiter is off there is no significant decay in the neon signals, it appears to make no difference to the pumping rate for argon whether the pumps are off or on. This shows that there is significant pumping of argon by the surface of wall or limiter. This is an important factor

causing the low fuelling rate.

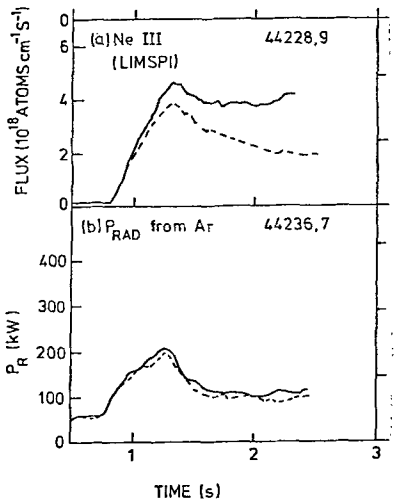

Figure 3: *Comparison of behaviour of (a) neon and (b) argon behaviour during and after gas puffing with ALTII open - - - - - and closed* ————

3. RESULTS FOR CO and CH_4

Global measurements show that for CO and CH_4 injection, the Z_{eff} increase is significantly lower than for neon with the same gas puff rate. Results for the time dependence of the main plasma parameters for CO injection are shown in fig. 4. The change in the carbon recycling rate at the limiter is not detectable above the noise level. A small rise in the oxygen level is detected. The rise in the radiation and Z_{eff} are much lower than in the case of neon. Although they are expected to be lower due to the slightly lower value of atomic number, it is found quantitatively that the fuelling rate of CO is <10%. The clear implication is that the recycling coefficient is much lower for carbon than for neon.

Direct observations of the point of injection show the parallel motion of the ionised species along the magnetic field. Some typical results are shown in fig. 5.[7] The spread of the neutral carbon CI is determined for given plasma conditions by the energy and angular distribution of the neutrals. The widths of the CII and CIII species are determined by parallel transport along the magnetic field direction and by the time required to ionise each species to the next higher state. The width decreases as the background plasma temperature increases.[8] The situation is more complex for the case of the molecular species,

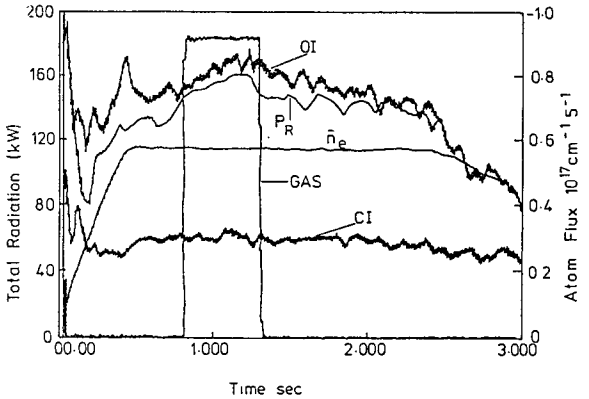

Figure 4: *Time dependence of radiated power, P_R, OI and CI at the limiter and electron density n_e during a 0.5 sec CO puff into a deuterium plasma in TEXTOR. I_p = 350kA, n_e = 2 x $10^{19}m^{-3}$.*

CO, than for the rare gases, since ionisation of the molecule is the most probable reaction.[9] The principle reactions for which there are data are shown in fig.

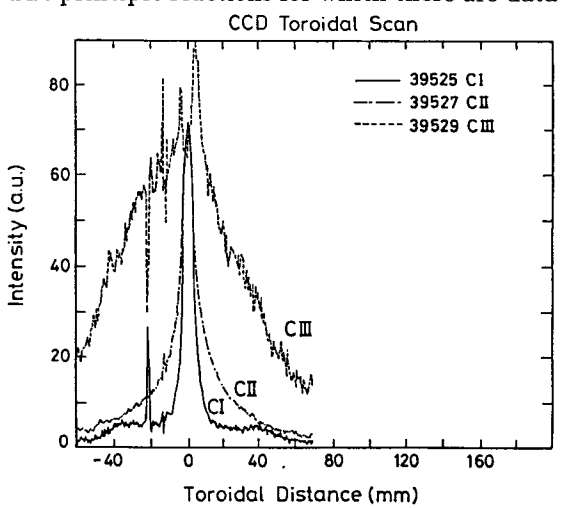

Figure 5: *Spatial distribution of carbon emission, CI, CII,CIII, along the magnetic field direction during CO puffing from a rail limiter at radius 46 cm in the TEXTOR tokamak.*

6 and compared with the cross–sections for ionisation of the atomic species.[10] Dissociative ionisation (to C^+ + O or O^+ + C) has a cross-section which is a factor of 6 lower than simple ionisation for the electron temperatures of

interest.[9] After ionisation to CO^+, the molecular ion must move along the magnetic field until it is dissociated. The dissociation occurs rapidly ($< 1\mu s$) as the cross-section is larger than for the original ionisation of the molecule.[10] No direct information is available on the energy of resulting atoms or ions from the dissociation of the CO^+, although there is a suggestion that it will result from the same state as the CO neutral molecule.[11] Energy distributions from the neutral molecule have been directly measured and are typically $\simeq$ 0.05eV.[12]

The spreading in the toroidal direction has been modelled using the

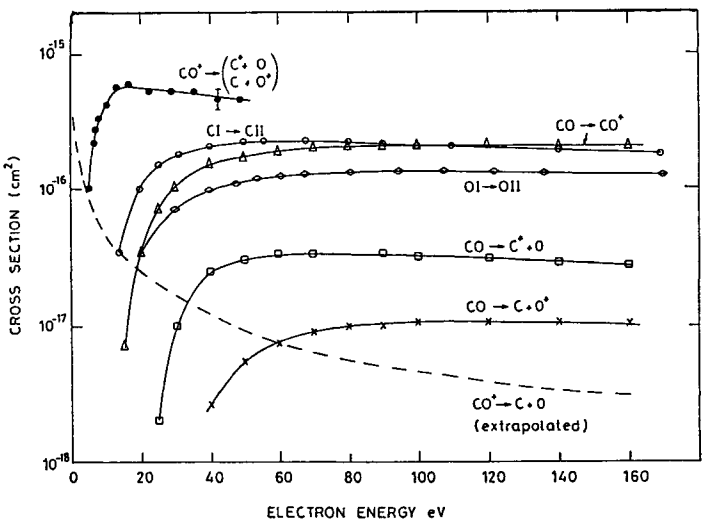

Figure 6: *Ionisation rates for various impact ionisation reactions in CO.*[9,10,11]

LIM Monte Carlo code.[13] The background density and temperature are taken directly from experimental measurements. Good fits to the experimental data can only be obtained if energies less than 0.1eV are used, consistent with the measured data for the neutral molecule.[12] The toroidal distribution of carbon from CH_4 and the oxygen and carbon from CO are compared in fig. 7. The spatial distributions are indistinguishable. This shows that the oxygen and carbon energies are approximately the same, as would be expected from momentum conservation and the nearly equal masses. It is also strong evidence that C from CH_4 has a low energy. This appears to be in contradiction with theoretical estimates which suggest that much higher energies may occur.[14] However, the complete dissociation of CH_4 is very complex, with many reaction chains, and the most probable energy is difficult to assess.

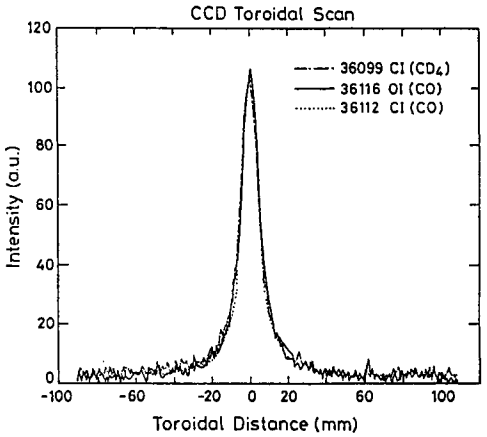

Figure 7: *The spatial distribution of CI from methane and CI and OI from CO during gas puffing through a limiter in the TEXTOR tokamak*

4. HEATING OF IMPURITY IONS

Impurity ions entering the plasma as gaseous species do so with low energy as discussed above. As soon as they are ionised, however, heating by ion-ion collisions starts. The amount of time an ion has in a given charge state before it is ionised to the next highest charge state is given by the ionisation time

$$\tau_{iz} = \frac{1}{n_e \overline{\sigma v}} \tag{3}$$

The characteristic heating time is given by classical rates[15]:

$$\tau_{th} = \frac{m_I T_B^{3/2}}{1.4 \times 10^{-13} m_B^{1/2} n_B Z_B^2 Z_I^2 \ell n \Lambda} \tag{4}$$

where m_I and m_B, Z_I and Z_B are the masses and charge states of the impurity and background plasma ions, n_B and T_B are the background plasma density and temperature and $\ell n \Lambda$ is the Coulomb logarithm. The thermalisation rate is

$$\frac{dT}{dt} = \frac{T_B - T}{\tau_{th}} \tag{5}$$

where T is the impurity temperature. Using equation (5) we can calculate the impurity ion temperature attained in a given charge state, before ionisation to the next higher state

$$T = T_B - (T_B - T_o) exp(-\tau_{iz}/\tau_{th}) \tag{6}$$

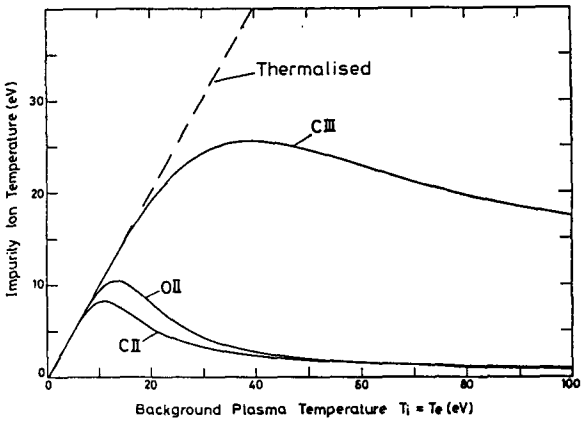

Figure 8: *Impurity ion temperatures, OII, CII and CIII calculated as a function of background plasma temperature in a deuterium plasma from equation 6.*

The ratio τ_{iz}/τ_{th} thus determines the fraction of the background plasma temperature which an ion gets to in a given charge state. It is seen that this is independent of density (assuming $n_B = n_e$) and dependent only on T_B (assuming $T_i = T_e$). The temperatures of a number of impurities, calculated on the basis of this simple model are shown in fig. 8. At low values of T_B, ionisation is slow but ion heating is rapid (being proportional to $T_B^{-3/2}$). Thus the impurity ions rapidly thermalize with the background plasma. On the other hand, at high plasma temperature ionisation is rapid and heating is slow. The impurity ions do not thermalize in the low ionisation stages.

Direct measurements of the impurity ion temperature during impurity gas puffing have been made by measuring doppler broadening with a high resolution spectrometer.[7] Although it is difficult to unfold the distribution, reasonable estimates of the temperatures can be made down to a few eV by folding together the instrument function, the structure of the Zeeman splitting in the known magnetic field, estimating an ion temperature and then fitting to the experimentally measured line width.

5. IMPURITY CHARGE STATE DISTRIBUTION

For impurities entering at a localized source it is clear that the low charge states will dominate close to the source. Ionisation to higher states takes longer and so the ions will have moved further from the source both toroidally, poloidally and radially.

With intrinsic impurities where the source is continuous throughout the discharge, the ions have time to diffuse into the centre and become highly

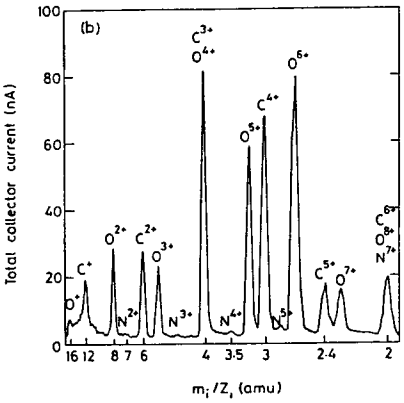

Figure 9: *Spectrum of mass/charge ratio for impurities in the DITE tokamak measured using a Plasma Ion Mass Spectrometer PIMS* [16] *in a deuterium plasma.*

stripped and heated. In equilibrium the inflow must be balanced by an equal flow outwards. Because recombination rates are slow compared with transport times, it is possible to get high charge states in the plasma boundary. This picture has recently been confirmed by measurements using a Plasma Ion Mass Spectrometer (PIMS).[16,17] A spectrum of mass/charge ratio is shown in fig. 9 for the intrinsic impurity ions in the DITE tokamak. Under the conditions studied, carbon and oxygen levels were high and approximately equal for the two species. It is observed that all charge states of the two impurities are present with the most probable ones being C^{4+} and O^{4+}. The charge state distribution has been compared with the LIM code calculations and rather good agreement obtained.[16]

6. SUMMARY AND CONCLUSIONS

Impurities entering a plasma are rapidly ionised and heated. These processes can be observed relatively easily with standard spectroscopic techniques. The observations also show transport along and across magnetic field lines. The heating and parallel transport are consistent with classical processes.

Ionisation in the plasma boundary can lead to collisions with the surfaces of wall and limiter. Where there is a high recycling coefficient (He, Ne) the impurities get into the plasma, probably by a random walk. This leads to long effective time constants determined mainly by the recycling coefficient R. The behaviour of such impurities can be described by a simple global model. Where the reflection coefficient is lower, e.g. argon and carbon, the effect is to reduce the fuelling rate in some cases by factors of ~ 100. This lower fuelling

rate should affect the impurity concentration of intrinsic impurities, though this effect has not been widely recognised.

The situation with intrinsic impurities is more difficult to analyse because they have a spatially distributed source with a wide range of incoming ion energies and angles. However, these can also be analysed with Monte Carlo techniques. In the steady state intrinsic impurities can diffuse to the centre and become highly stripped. They can then diffuse out to the wall. Because recombination is generally slow compared with diffusion transport times, impurities with high ionisation states can be observed at the wall.

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