INFLUX AND SOURCES OF MEDIUM- AND HIGH-Z INTRINSIC IMPURITIES IN THE ALCATOR C TOKAMAK

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ABSTRACT. The influx of heavy impurities in the Alcator C tokamak is determined as a function of plasma parameters from observations of intrinsic impurities, in conjunction with an empirically derived anomalous impurity diffusion model. The influx of molybdenum as a function of electron density is found to decrease dramatically as the electron density is raised above $1 \times 10^{14}$ cm$^{-3}$. Sputtering (by neutrals, ions and impurities) is probably the dominant molybdenum release mechanism in Ohmically heated discharges.

1. INTRODUCTION

Heavy impurity densities must be minimized in fusion reactors because of the radiation cooling they would cause. While the very long impurity confinement time predicted by neoclassical theory is generally not observed in reasonably clean, Ohmically heated tokamak discharges, it would be desirable not to have impurities in the first place. This requires an ability to control the impurities at their source. In order to limit the source, the physical origins of impurities at the plasma edge must first be located and attempts made to understand the mechanisms responsible for impurity generation there. In plasmas with strong auxiliary heating, long impurity confinement times are sometimes observed [1]. If these cases are unavoidable, it becomes extremely important to reduce the impurity influx. It is the purpose of this study to utilize observations of intrinsic impurities in the Alcator C tokamak for obtaining a better understanding of the plasma/wall interactions and the resultant impurity generation and influx into the hot core of tokamak plasmas.

If the transport which takes impurities from the edge to the interior plasma is understood, then their source can be characterized from observations of these impurities in the plasma. An empirical impurity transport coefficient, determined from a series of trace impurity injection experiments, and a computer code used to model these results are reviewed in Section 2. Observations of intrinsic molybdenum, chlorine and sulphur are presented in Section 3. The deduced scalings of the influx of these impurities are presented in Section 4. Comments on the effects of changes in edge-plasma parameters are given in Section 5, and some speculations about the mechanisms which remove the impurities from the walls and limiters are offered in Section 6. Concluding remarks are given in Section 7.

2. REVIEW OF IMPURITY INJECTION EXPERIMENTS ON ALCATOR C

A series of impurity injection experiments was performed on the Alcator C tokamak [2] in order to determine the nature of impurity transport. The results of these injections were found to be inconsistent with the predictions of pure neoclassical impurity transport [3]. The observations were, however, well described by a model which includes only the effects of self-diffusion. The density of a particular ionization state can be found from the following equation:

$$\frac{\partial n_j}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} \left( r \Gamma_j \right) + n_e \left[ s_{j-1} n_{j-1} - s_j n_j + \alpha_j n_{j+1} - \alpha_{j-1} n_j \right] + \text{[source]}_{j=1}$$

with the flux given by

$$\Gamma_j = -d \frac{\partial n_j}{\partial r}$$

where $s_j$ is the ionization rate from the j-th state and $\alpha_j$ is the recombination (radiative and dielectronic)
rate to the j-th state. The code predictions (Eqs (1) and (2)) use a delta-function source to model the injection process. The observed time histories of particular charge states yield the anomalous impurity diffusion coefficient, \( d \), whose scalings with plasma parameters are found to be

\[
d (cm^2 \cdot s^{-1}) = \frac{2300 a_L q_L}{R^{0.75} m_{bg}} (Z_{bg}/Z_{eff})
\]

where \( a_L \) and \( R \) are the minor and major radii (in cm), \( q_L \) is the limiter safety factor, \( m_{bg} \) is the background ion mass (in amu), \( Z_{bg} \) is the background ion charge and \( Z_{eff} \) is the effective charge of the plasma due to intrinsic impurities. This diffusion coefficient is independent of electron density, provided there are only low levels of MHD activity. In addition, the coefficient does not depend on the charge and mass of the impurity, provided the presence of the impurity does not disturb the macroscopic plasma parameters. While the dependences on major radius and \( Z_{eff} \) should not be taken as strict scaling laws, the other variations are quite well established empirically. Thus, from a known source and a measured impurity emission the impurity transport was determined. Alternatively, given the impurity transport and the measured impurity emission, the source of intrinsic impurities can be characterized.

3. OBSERVED SCALINGS OF MOLYBDENUM, CHLORINE AND SULPHUR

Intrinsic impurity emission from Alcator C is routinely monitored with a flat crystal X-ray spectrometer employing a PET crystal (1 Å < \( \lambda < 8 \) Å) and with a 1 m grazing-incidence monochromator (40 Å < \( \lambda < 550 \) Å). The dominant medium- and high-Z impurities are molybdenum, chlorine, sulphur, chromium and iron [4–6]. Data have been collected under a wide range of operating conditions: \( 10^{13} \) cm\(^{-3} \) < \( n_e \) < \( 10^{15} \) cm\(^{-3} \); 200 kA < \( I < 700 \) kA; 60 kG < \( B_T < 120 \) kG; in hydrogen, deuterium and helium working gases; and with three limiter configurations (10 cm molybdenum, 16.5 cm molybdenum and 16.5 cm graphite).

A typical scaling of molybdenum emission as a function of electron density is shown in Fig.1. The steady-state brightness at 77 Å, in the middle of a quasi-continuum of lines due to charge states near Mo\(^{25+} \) [7, 8], is plotted for a sequence of 200 kA,

\[
\text{FIG. 1. Brightness at 77 Å (~Mo}\,^{25+}\text{), as a function of average electron density, at constant current, with 10 cm molybdenum limiters.}
\]

\[
\text{FIG. 2. Brightness at 5.2 Å (~Mo}\,^{32+}\text{), as a function of electron density, at constant current, with 16.5 cm graphite limiters.}
\]

\[
\text{FIG. 3. Time histories of helium-like chlorine and sulphur for two successive discharges, as well as the electron density and the central soft-X-ray emission.}
\]
120 kG deuterium discharges. In this case, the minor radius was 10 cm, defined by a molybdenum limiter, and the wall-to-limiter distance was 9 cm. The molybdenum brightness rapidly increased with decreasing electron density below about $2 \times 10^{14}$ cm$^{-3}$. Reduction of metallic impurity emission as the electron density increased was also observed in other tokamaks [9—11]. A similar situation is inferred from the X-ray observations, as depicted in Fig.2. The brightness, with the background subtracted, at 5.2 Å (2p–3s transition [6, 12, 13] in Mo$^{3+}$), is shown as a function of electron density for a series of discharges at 415 kA and 80 kG in deuterium. In this example, the minor radius was 16.5 cm and the limiter material was graphite, indicating that the source of molybdenum was either the walls ($r = 19$ cm) or the virtual limiters ($r = 17.5$ cm). The graphite limiters were installed after about three years of operation with molybdenum limiters. The overall level of molybdenum emission was about a factor of 20 lower than in the case with a molybdenum limiter. Still, there was a marked increase in molybdenum brightness below electron densities of $2 \times 10^{14}$ cm$^{-3}$. This increase was accompanied by rapid increases in total radiated power [14], $Z_{eff}$ and electron temperature.

The behaviour of chlorine is somewhat different. Shown in Fig.3(a) are the time histories of helium-like chlorine (4.44 Å), the central-chord line-averaged electron density ($0.58 \times 10^{14}$ cm$^{-3}$/fringe) and the central-chord soft-X-ray brightness ($\nu \sim 1$ keV). The chlorine brightness seems to follow the electron density and is nearly constant between 150 and 375 ms. A similar behaviour of chlorine emission was observed in TFR [15]. The case of helium-like sulphur (5.039 Å) shown in Fig.3(b) for a similar (the next) discharge is in contrast to this. Here the emission seems to track the soft-X-ray signal (also the molybdenum signal), increasing monotonically until 350 ms. The atomic processes of the two adjacent ions are similar, and the transport has been shown to be independent of impurity species. The physical source of these impurities may be the same, since the signal levels of both sulphur and chlorine dropped by a factor of eight or so when the limiter was changed from molybdenum to graphite. The difference in the time histories of their helium-like emissions must be due to differences in the mechanisms responsible for their removal from the same surfaces.

The scaling of the helium-like chlorine signal with electron density is shown in Fig.4 for deuterium discharges with a 10 cm molybdenum limiter. Toroidal magnetic field and plasma current were kept constant over this density scan. In contrast to the molybdenum scaling, the chlorine brightness increases nearly linearly with electron density for $n_e > 2 \times 10^{14}$ cm$^{-3}$. It is difficult to measure emission from helium-like chlorine below this density since there are molybdenum lines at the same wavelength which dominate. In contrast, there are no molybdenum scaling data shown above $2.5 \times 10^{14}$ cm$^{-3}$, since molybdenum radiation is undetectable above the X-ray continuum.

The variation of the X-ray molybdenum brightness at 5.2 Å as a function of plasma current is shown in Fig.5 for a series of 100 kG deuterium discharges at an electron density of $1.4 \times 10^{14}$ cm$^{-3}$. There is a strong increase in the molybdenum brightness as the current is raised from 250 to 600 kA. It should be noted that as the current is increased, the central}

![FIG.4. Brightness of helium-like chlorine as a function of electron density. The predicted brightness, assuming a chlorine influx which is independent of electron density, is also shown by the solid line.](image)

![FIG.5. Brightness of neon-like molybdenum as a function of plasma current, at constant electron density, with 16.5 cm graphite limiters.](image)
electron temperature, the width of the electron temperature profile and the impurity confinement time all increase. As before, the limiters were 16.5 cm graphite.

4. DETERMINATION OF THE MOLYBDENUM AND CHLORINE INFUXES

Since impurity transport is independent of electron density, the brightness of chlorine might be expected to increase linearly with \( n_e \), provided the chlorine source is also independent of electron density. This is just what is predicted by the transport code described above, assuming a steady-state impurity source independent of \( n_e \). The predicted brightness is shown in Fig.4 by the solid line. In this case, the diffusion coefficient, \( d \), from Eq.(3), was 1100 cm\(^2\) s\(^{-1}\). The chlorine influx was taken to be independent of electron density and the measured changes in the electron temperature were included.

The case of molybdenum shown in Fig.5 is in contrast to the case of chlorine shown in Fig.4. Since the anomalous diffusion coefficient in Eq.(3) is proportional to the limiter safety factor, the impurity confinement time increases with plasma current. It might be expected that the molybdenum brightness correspondingly increases with plasma current. Although this notion is qualitatively similar to the observations of Fig.5, a slight variation of the molybdenum influx with plasma current is required to achieve quantitative agreement. By scaling the diffusion coefficient with the current in accordance with Eq.(3), and incorporating the appropriate changes in the electron temperature and profile in Eq.(1), the molybdenum source was adjusted to comply with the data of Fig.5. The result for the variation of the influx as a function of plasma current is shown in Fig.6. There is a slight decrease in the influx with increasing current but, as will be shown later, changes of this magnitude are not considered significant within this model. The conclusion here is that the increase of molybdenum brightness with increasing plasma current can be mostly accounted for by the increase in impurity confinement with plasma current in accordance with Eq.(3).

The dependence of molybdenum influx on electron density can be obtained from the data of Fig.1 or Fig.2 by following a procedure similar to that described above. The molybdenum influx, shown as a function of electron density in Fig.7, is obtained from the data of Fig.2. There is a strong decrease in the molybdenum influx as the electron density increases from

--- from 77 Å
--- from 5.2 Å

FIG.8. Molybdenum influx as a function of electron density, with molybdenum limiters, from the data shown in Fig.1, as well as from the case with a 16.5 cm molybdenum limiter.
1 X 10^{14} \text{ cm}^{-3} to 2 \times 10^{14} \text{ cm}^{-3}. Above this density, the magnitude of molybdenum radiation is less than the background. The apparent turnover of the molybdenum influx below $n_e = 1 \times 10^{14} \text{ cm}^{-3}$ should not be taken too seriously, as effects of this magnitude may be due to changes in edge conditions and uncertainties in the temperature profile. A similar situation is obtained from the data of Fig.1 for the 10 cm molybdenum limiter. This is shown in Fig.8, together with some additional results from X-ray observations using a 16.5 cm molybdenum limiter. The qualitative trends in Figs 7 and 8 are the same, although the location of the source for Fig.7 was the vacuum chamber walls and/or virtual limiters, while in Fig.8 the source was mainly the limiter. The overall level of molybdenum emission, in otherwise similar discharges, is a factor of about 20 greater with molybdenum limiters than with graphite limiters.

When the background gas was changed from deuterium to helium (with $n_e = 2.4 \times 10^{14} \text{ cm}^{-3}$, $I_p = 300 \text{ kA}$ and $B_t = 80 \text{ kG}$), the molybdenum brightness at 5.2 A increased by a factor of four. Accounting for the enhancement of impurity confinement as the background ion mass is increased (Eq.(3)) (as well as accounting for the slight increase in electron temperature), the predicted increase in signal is about a factor of six, in rough agreement with what is observed. This indicates that the molybdenum influx is not strongly dependent on the background ion, in changing from deuterium to helium, although there is a slight decrease.

Different models for the impurity flux (Eq.(2)), in particular those including an inward convection term [16, 17], may also be considered. Convection was not found to be important for explaining the Alcator C impurity injections in the majority of cases. Inclusion of inward convection, consistent with the injection experiments, in the determination of the intrinsic molybdenum influx would not qualitatively alter the conclusion of a strong increase of molybdenum influx at the lower electron densities.

5. EFFECTS OF EDGE ASSUMPTIONS

The above conclusions concerning the impurity influx are uncertain by about a factor of two because of uncertainties in the edge-plasma conditions. Changes in the edge electron density and temperature profiles affect the shape of the deposition profile of the incoming neutral impurities. A typical case for molybdenum is shown in Fig.9, for which the ionization rates for Mo from Ref.[18] were used in conjunction with probe measurements of the edge electron density and temperature profiles [19]. This spatial distribution of the singly ionized impurity (which is also a function of the energy distribution of the incoming Mo) is an initial condition for the transport code (Eq.(1)). Variations of this initial profile subsequent to reasonable changes in edge conditions can lead to deviations in the central impurity densities of up to a factor of two. While this could account for the scaling with plasma current deduced in Fig.6, the conclusions regarding the dependence of the molybdenum influx on electron density remain qualitatively unchanged (except for the apparent turnover below $n_e = 1 \times 10^{14} \text{ cm}^{-3}$ in Fig.7).

6. INTERPRETATION OF THE INTRINSIC IMPURITY SOURCES

There are several mechanisms [20] which could remove molybdenum from the walls, limiter and virtual limiters. These include evaporation, physical and chemical sputtering by plasma and impurity ions and neutrals, arcing, blistering and electron desorption. Evaporation of the limiter can occur because a substantial portion of the Ohmic heating input is deposited there during each shot. The power density at the limiter during a shot increases linearly with the electron density of the discharge, going from about 250 W cm$^{-2}$ at a density of $1 \times 10^{14} \text{ cm}^{-3}$ to 900 W cm$^{-2}$ at $2 \times 10^{14} \text{ cm}^{-3}$ [14]. More evaporation, and hence more molybdenum influx, would be expected as the density is raised, in contrast to what is observed in Fig.8, indicating that evaporation due to the thermal edge
plasma is not the primary molybdenum introduction process, at least in non-disruptive discharges. Evaporation induced by runaway electrons is a candidate process since sometimes molybdenum influx and hard-X-ray production occur simultaneously for plasmas of low electron density. There is not, however, always a good correlation between hard-X-ray production and molybdenum influx.

Non-thermal electrons, generated by RF waves, may be instrumental in introducing impurities during RF heating and current drive experiments [21, 22]. Processes such as arcing and blistering presumably introduce molybdenum in discrete bursts in time, a situation similar to the impurity injection experiment. In fact, such 'natural injections' are seen to occur, as shown in Fig. 10. While these events are occasionally observed, they do not result in a steady level of molybdenum emission, which is the routine state of affairs. Sputtering by neutrals is a possible molybdenum release mechanism, since the observed neutral flux at energies of >1 keV increases dramatically [23] as the electron density is reduced to below $2 \times 10^{14}$ cm$^{-3}$. This increase in the neutral flux will give rise to more sputtering and an increase in the molybdenum influx, in qualitative agreement with Figs 7 and 8. However, since the molybdenum influx did not change dramatically when the background ion was changed from deuterium to helium, it can be concluded that sputtering by neutrals is not the dominant mechanism in this case. The outflux of energetic neutral helium is much less than the neutral deuterium outflux [23]. The remaining primary candidate for the dominant molybdenum release mechanism is sputtering by ions and impurities. Molybdenum sputtering coefficients are rapidly increasing functions of ion temperature. The edge electron temperature and presumably the edge ion temperature increase as the electron density is lowered, presumably giving rise to an increased molybdenum influx.

A 1-D edge model [24] was constructed to explore this hypothesis. The molybdenum sputtering rate due to the flux of background ions to the limiter can be calculated, given the edge-plasma measurements of electron density and temperature as well as power to the limiter. Ion and electron temperatures are assumed to be equal. The determination of the sheath potential follows Ref. [25] and sputtering coefficients are evaluated for a given ion energy, mass and charge using DSpot [26].

The calculated molybdenum influx as a function of electron density is shown in Fig. 11 for a deuterium plasma with a 16.5 cm molybdenum limiter. The molybdenum influx, deduced from emission at 5.2 A in conjunction with the impurity transport model (Fig. 8), is shown by line A. Line B is the calculated curve for deuterium ions incident on a molybdenum limiter. Although the density dependence is similar for these two source predictions, the discrepancy in
magnitude cannot be accounted for by the uncertainties in the models. Line C shows the effect of including self-sputtering by molybdenum ions. In this case the agreement is reasonable. The increase of the molybdenum influx as the working gas is changed from hydrogen to deuterium may be accounted for by the increase of the sputtering coefficient as the ion mass is increased. The two major uncertainties in this edge model are the strong dependence of the sheath potential on the plasma species at the sheath and the assumption of equal ion and electron temperatures at the edge.

The location of the molybdenum source when operating with a graphite limiter must be the virtual limiters and/or the walls. The electron temperature near these surfaces is low (about 5 eV), so sputtering by background ions is unlikely. Sputtering by neutrals and subsequent self-sputtering by molybdenum is probably the dominant process under these circumstances. The calculated molybdenum influx due solely to neutral sputtering is shown by line D in Fig. 11. The charge-exchange flux to the walls was computed using the FRANTIC [27] code, and molybdenum was assumed to cover 10% of the walls.

The apparent independence of the chlorine influx on electron density could be due to a combination of competing processes. In particular, the chlorine source could be due mainly to two processes: thermal desorption, which would increase with increasing electron density, since the heat load to the limiter increases; and sputtering, which would decrease with increasing electron density.

7. CONCLUSIONS

Observed intrinsic impurity emission has been combined with an empirically determined transport model in order to characterize the source of impurities in Ohmically heated discharges. The influx of molybdenum is found to increase dramatically as the electron density is lowered below $2 \times 10^{14}$ cm$^{-3}$. The primary location of the origin of molybdenum, sulphur and chlorine is the molybdenum limiters. The dominant mechanism which removes molybdenum from the limiters is believed to be physical sputtering by plasma ions and self-sputtering by molybdenum.

ACKNOWLEDGEMENTS

The authors would like to thank the entire Alcator C group for support and co-operation during these experiments, in particular D. Gwinn and R. Parker for operating the machine, S. Wolfe and R. Gandy for electron density and temperature measurements, B. LaBombard for edge probe measurements, C. Fiore for neutral flux information and K. Chamberlain for assistance in the data reduction.

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(Manuscript received 5 October 1983
Final manuscript received 2 February 1984)