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PROBE MEASUREMENTS OF IMPURITIES IN THE PLASMA BOUNDARY OF PLT*

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ABSTRACT

Carbon probes were exposed to the plasma edge in PLT at various distances from the plasma and to different numbers (1, 2, 3, 6, 12) of overlaid discharges. The type and areal density of impurities retained were determined using ion backscattering. The principal impurities with $Z > 6$ were found to be O, Fe, Cr, Ti, and Cu in decreasing order of abundance. Fluxes for these impurities at a position close to the wall were found to be respectively 14, 2.8, 0.8, 0.6 and $0.2 \times 10^{15}/\text{cm}^2$ ($\pm 25\%$) respectively, compared to the value $2.2 \pm .5 \times 10^{17} \text{ D}/\text{cm}^2\text{s}$ for the deuterium flux at this position. Lateral spreading of the impurity deposition profile behind the probe slit allowed a lower limit to be placed on the impurity mean ion energy. Between the wall and radius of the ring limiter the impurity fluxes increased by a factor of ~ 2 compared to an increase in the D flux by a factor of ~ 5 . Since impurity and deuterium fluxes were both measured the effect of sputtering by the incident deuterium on the impurity accumulation can be assessed.

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The observed nonlinear impurity retention versus number of discharges is consistent with the values determined for the impurity and D fluxes and the expected effects of sputtering. The observed large flux of iron at the radius of the ring limiter indicates that this is a primary source of metal impurities in PLT.

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1. INTRODUCTION

In recent years significant advances have been made in reducing the impurity levels in magnetically confined plasmas and much has been learned about the effect of impurities on discharge characteristics. However, the evidence indicates that in many present day tokamaks a substantial fraction of the energy loss is still due to radiation by impurities and that further improvements in plasma purity are necessary in order to achieve plasma conditions required for a tokamak reactor [1].

In order to identify the dominant mechanisms by which impurities are introduced to the plasma, diagnostic studies are needed of the impurity flow at the plasma edge, where the impurities originate. Such studies help to evaluate the effect on impurity production of different machine designs, operating conditions, auxiliary heating methods, and special techniques to control impurities such as Ti gettering, gas puffing, and use of divertors.

One technique which is now being used to study impurities in several machines is to collect the impurities on a passive probe inserted into the plasma edge [1-6]. In the study described here we have exposed carbon probes to different numbers of discharges and at several radial positions between the wall and limiter radii in PLT. The elemental species and number of impurity atoms retained were subsequently determined using Rutherford backscattering spectroscopy (RBS). From this data the flux of impurities at the

plasma edge was estimated as a function of distance from the plasma. The flux and temperature of deuterium incident on the same probes were also determined [7], and compared to the impurity fluxes. These studies have provided one of the most complete determinations of particle fluxes at the plasma edge and allow conclusions to be made about the origin of the impurities.

2. EXPERIMENT

2.1 Probe Exposures

The material used for the samples in this study was Papyex carbon. Carbon has several qualities which make it especially well-suited for this application: 1) due to the low atomic weight the reflection of incident ions is lower than for most other materials, the sticking probability is close to unity for low fluences of heavy ions; 2) the low atomic weight and clean oxide-free surface allow high sensitivity RBS analysis; and 3) at temperatures below 400°C carbon traps incident hydrogen to high concentrations. In the present study, a set of 7 carbon samples were mounted on a grounded cylindrical holder 3 cm in diameter. Surrounding this was a cylindrical tantalum shield with 3 mm wide slits on opposite sides. The distance from the slit to the samples was 3mm. This assembly (illustrated schematically in Fig. 1) was placed into the PLT vacuum vessel through the north neutral beam port. The exposure position was in the midplane of the torus such that the sample nearest the plasma was just inside the radius

of the stainless steel ring limiter which was 45 cm from the minor axis of PLT. Because of limited access it was necessary to position the probe such that there was a 41° angle between the toroidal field direction and the normal of the sample surface. The plasma minor radius was determined by top and bottom carbon mushroom limiters at $r = \pm 40$ cm. The C and SS limiters were 140 and 160 degrees, respectively, around the torus from the probe in the direction of the toroidal field and plasma current. The position of the plasma center was feedback stabilized at $R = 135 \pm 2$ cm, ~ 3 cm outside the minor axis of PLT. By rotating the sample holder between discharges behind the fixed slit apertures selected regions of the sample were exposed to different discharges. In addition to single discharges, overlaid exposures to 2, 3, 6, and 12 discharges were made. The discharges were low density deuterium discharges typical of those used for ion cyclotron resonant frequency heating, although no auxiliary heating was applied during the exposures. The plasma parameters were: $I_p = 250$ kA, $\bar{n}_e = 0.9 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) = 1.1$ keV, $B_T = 17$ kG, $V_L = 1.6$ V and the pulse duration was 0.4 sec.

2.2 Results

Following the exposures the samples were air transferred to a chamber for RBS analysis using 2 MeV ^4He from a Van de Graaff accelerator. The main impurities deposited during the exposure were found to be O, Fe, Cr, Ti, and Cu in decreasing

order of abundance. Some Ta was also observed which presumably came from the probe slits. Fig. 2 shows an example of the amount of impurities retained on the carbon as a function of distance along the strip. Also shown for comparison is the amount of deuterium retained on the strip. The regions which were located beneath the slit during the exposures are indicated at the bottom of the figure. The distance between the centers of adjacent exposed areas was 5 mm, compared to the 3 mm slit width. However, it can be seen that there was still considerable overlap between adjacent exposures. This broadening of the deposition profiles indicates that the ion gyroradii R_L are of the order of or greater than the slit width. In the limit where $R_L \gg 3$ mm the ion trajectories are not significantly affected by the B field over the distance from the slits to the carbon and the lateral deposition profile would be that for free streaming particles through a slit aperture (effusion) shown by the dotted line. Since the shape of the impurity deposition profiles is similar to the effusion profile the impurity ion gyroradii must be ≥ 3 mm which requires ion energies in the plasma ≥ 20 eV for Fe^+ and ≥ 70 eV for O^+ and correspondingly higher energies for multiply charged ions.

Fig. 3 shows the peak areal density of impurity atoms retained on the exposed regions of two of the samples, as a function of number of overlaid exposures. The accuracy of these values is estimated to be $\sim \pm 25\%$. (These data

were taken on probes exposed facing $\bar{I}_p$ the ion drift direction.) For the sample located at 50.4 cm, close to the wall radius, the amount of impurities increases fairly linearly with increasing number of discharges.

The following values for the impurity fluence to the sample surface per discharge at $r = 50.4$ cm were obtained from the slope of these curves: 2.6, 0.5, 0.14, 0.11, $0.03 \times 10^{15}/\text{cm}^2$ for O, Fe, Cr, Ti, and Cu respectively. Assuming a deposition profile for effusive flux through the slit this represents impurity fluxes at the slit of 14, 2.8, 0.8, 0.6, $0.2 \times 10^{15}/\text{cm}^2 \text{ s}$ ($\pm 25\%$) for the above species. The sample located at 46.6 cm shows a larger initial accumulation of impurities than the sample at 50.4 cm, however, at higher numbers of discharges a saturation behavior is observed. It should be noted that the impurity fluxes on the electron drift side of the probe (side facing away from $\bar{I}_p$) were about a factor of 2 lower than on the ion drift side for the same distance from the plasma. This was also true for the D flux [7]. This may be because the limiters were closer to the electron side of the probe.

The oxygen retention is probably due to physical implantation rather than chemical gettering by deposited metals since the ratio of oxygen to metal atoms retained is > 4 . However, oxygen ions with energies of the order 100 eV would have a range of only a few interatomic distances in carbon and thus the oxygen retention in this layer would be expected to saturate as is observed in Fig. 3. This

is consistent with the behavior observed for hydrogen implanted in carbon where a detailed understanding of the saturation behavior has allowed the hydrogen energies and fluxes to be determined [7].

2.3 The Effect of Sputtering on Impurity Accumulation

From analysis of deuterium retention [7] on this probe ($r = 50.4$ cm) the deuterium flux was found to be $2.2 \pm .5 \times 10^{17}$ D/cm² s with an ion temperature of 200 ± 50 eV. Since the sputtering yield for D of this energy incident on carbon [8] is comparable to the observed ratio (0.013) of Fe to D fluxes to the probe, the impurity retention on the probe might be affected by sputtering. The process of sputtering as a means of removing deposited impurity atoms has been previously discussed [2], but our study is the first in which deuterium and impurity fluxes have been determined simultaneously allowing an assessment of sputtering by the deuterium. The effect of this on the impurity retention depends on the ratio of Fe to D fluxes and can be considered in two regimes. First, for the case where the incident D flux ϕ_D is high enough such that the removal of surface atoms by D sputtering balances the incident impurity flux ϕ_i the rate $\dot{n}_i$ at which impurity atoms accumulate near the surface is given by

$$\dot{n}_i = \phi_i - \phi_D \sigma_i \quad (1)$$

where σ is the cross section for sputtering an impurity atom from the surface. Assuming that σ is independent of the near surface composition the rate of impurity accumulation is initially just equal to ϕ_i but n_i exponentially approaches a steady state coverage $n_o = \frac{\phi_i}{\phi_D \sigma}$ by the time several atomic layers have been removed ($\phi_D \sigma t \geq 1$)

$$n_i = n_o \left(1 - e^{-\phi_D \sigma t} \right) . \quad (2)$$

The cross section σ is difficult to estimate for heavy atoms on a light substrate and a distribution of energies and angles of incidence for the incident D, but we can get a rough estimate by assuming $\phi n_i = S$ when n_i is two monolayers (i.e. $n_i = 5 \times 10^{15}/\text{cm}^2$) where S is the sputtering yield (atoms removed per incident D) for a bulk material. For deuterium incident on carbon or stainless steel with a Maxwellian energy distribution with $kT = 200$ eV (but normal incidence) $S = 10^{-2}$ [8] (see reference [9] for measurements of the angular dependence of sputtering yields for low energy light ions). This gives $\sigma = 2 \times 10^{-18} \text{cm}^2$. For the range of D fluxes incident on these probes ($\phi_D \sim 2 \times 10^{17} - 10^{18} \text{D}/\text{cm}^2 \text{s}$) n_i should approach a steady state behavior when $\phi_D \sigma t \geq 1$, i.e. when the number of discharges $\geq 3 - 10$. Since we observe that $\phi_i \sim \phi_D S$ the steady state coverage might be expected to be of the order of a

monolayer. It will be seen that some of the exposed probes showed evidence of this type of behavior. For the second case in which the removal of surface atoms by sputtering in the steady state is less than the incident impurity flux the next impurity accumulation rate will again be equal to the incident impurity flux initially, but exponentially approach an accumulation rate equal to the difference between the incident flux and removal rate.

These considerations have neglected the additional effect of sputtering by the incident impurities themselves. Although the impurity fluxes are much lower than the deuterium flux, the sputtering yields are expected to be higher because of their higher mass such that the resulting removal rate due to sputtering by impurities could be significant. It is difficult to assess the magnitude of this effect because of uncertainties in the ion energies and in the sputtering yield for heavy ions on composite targets at low energies.

A critical analysis of the impurity retention data shown in Figs. 3 and 4 gives an indication of the extent to which sputtering has affected the impurity accumulation on the probes. From the data shown in Fig. 3 it can be seen that at $r = 50.4$ cm the amount of impurities increased fairly linearly with increasing number of discharges up to 12 discharges. This indicates that here sputtering was not grossly affecting the impurity accumulation.

At $r = 46.6$ cm the amount of all impurities retained for one discharge was higher than at $r = 50.4$ indicating higher incident impurity fluxes; however, the amount retained after 12 discharges was not much greater than at $r = 50.4$. This suggests that on this sample, sputtering may be affecting the impurity accumulation at the larger numbers of discharges. However, since the amount of impurities retained for 1 shot was much less than the amount for 12 shots (i.e. $n_1 \ll n_0$ in eq. 2), the net impurity fluxes observed for the 1 shot exposure should be fairly close to the actual incident fluxes. This illustrates the importance of measuring the fluence dependence of the impurity retention.

Figure 4 shows the variation in the impurity deposition on the samples with distance from the plasma for O, Fe, and Ti. The impurity levels all drop very abruptly at the sample furthest from the plasma, presumably due to the shadowing effect of the wall. The retention of all impurities generally increases with decreasing distance from the plasma for the one shot exposures indicating that the impurity fluxes are higher closer to the plasma. The 3 discharge curve for the iron shows a dip beginning to develop at $r = 45$ cm. By 6 and 12 discharges this dip has become more noticeable and extended to positions further out from the plasma. The 12 discharge curves for O and Ti show a similar behavior. The appearance of this dip at the higher fluences may be an effect of sputtering. Between $r = 50.4$ and $r = 45.3$ the D flux increased by a factor of ~ 5 and its energy also increased by a factor of ~ 3 . The Fe flux (determined from the one shot exposure) only increased by

a factor of ~ 2 . This could produce a shift in the balance between deposition and erosion causing the saturation behavior described earlier for the impurity retention at positions closer to the plasma. This would give precisely the kind of behavior shown in Fig. 4. The abrupt increase in impurity deposition at $r = 44$ cm must then be due to an abrupt large increase in the impurity flux inside the ring limiter radius, which would swing the balance back in favor of impurity retention.

The general features of the impurity retention can be seen more easily in Fig. 5 which shows both the flux dependence and radial dependence of the impurity retention for the case of iron. Some smoothing of the data has been necessary in order to draw this 3 dimensional figure but the general trends are more clearly illustrated.

3. SOURCES OF IMPURITIES

Some conclusions can be drawn about the origin of the impurities from the relative fluxes of the various ion species and the variations in fluxes with distance from the plasma. For example, the ratio of the Cr to Fe fluxes to the probe was observed to be $0.28 \pm .05$. This is close to the composition ratio of 304 stainless steel ($\text{Cr/Fe} = .25$) and indicates that a stainless steel component is the source of these impurities. Also, the fact that the Fe flux to the probe was much larger than the Ti flux ($\text{Fe/Ti} \sim 5$) indicates that sputtering from surfaces coated by

Ti gettering, is not the major source of impurities. Impurity production due to sputtering or arcing on the stainless steel ring limiter would be consistent with these observations. The large Fe flux at $r = 44$ cm also points to the ring limiter as a major source of Fe. The sputtering here would be high due to the high ion fluxes and temperatures. An Fe atom sputtered from the limiter would quickly become ionized by electron impact. Subsequent outward radial motion would lead to the impurity ion being scraped off by the limiter. This would result in a high Fe flux close to the limiter radius as observed. Successive sputtering and redeposition could result in a net migration of these impurities to positions further out. The observation that the Fe deposition on the sample at $r = 44$ cm is fairly linear up to coverages of ~ 4 monolayers suggests that the sputtering of Fe on a carbon substrate is less than the sputtering yield of bulk stainless steel where these impurities originate. It should be added that some of the Fe deposited between wall and limiter radii could be due to sputtering at the wall. Sputtering rates are much lower at the wall than at the limiter because of the lower ion fluxes and energies, but the surface area is much larger. Because of the lower plasma density at the wall these impurities could travel some distance toward the plasma before being ionized.

The sources of the other impurities are less easy to identify. The Ti probably comes from internal components

exposed to the previous Ti gettering, and oxygen may come from sputtering, ion induced desorption or chemical erosion of oxide layers on Ti and stainless steel surfaces. The origin of the Cu has not been established. It may be due to redistribution of Cu from the neutral beam injectors which were used in earlier runs and have been previously shown [10] to sometimes contain low levels of Cu impurities in the beam. Another possible origin is a Cu microwave horn which was present.

4. CONCLUSIONS

Analysis of impurities collected on probes exposed to the plasma edge in PLT has provided a detailed picture of the flow of impurities in the plasma edge. The following conclusions can be made from this study: 1) the principal impurities with $Z > 6$ were found to be O, Fe, Cr, Ti, and Cu in decreasing order of abundance, 2) the observed lateral spreading of the impurity deposition profiles behind the slit aperture indicates incident ion energies ≥ 20 eV for Fe^+ and ≥ 70 eV for O^+ in the plasma edge, 3) retention increased linearly with number of shots for ≤ 3 shots and larger distances from plasma but tended to saturate at larger numbers of discharges and closer in to the plasma, 4) this behavior is expected when impurity retention is determined by a balance between deposition and sputtering of surface atoms. Analysis of this behavior shows that the net impurity fluxes observed for the 1 shot exposures should be close

to the actual incident impurity fluxes, 5) the fact that the D energies and fluxes to the probe were determined for the same set of discharges allowed direct comparison between the impurity and deuterium fluxes. Between the wall and limiter radii the impurity fluxes increased by a factor of ~ 2 whereas D fluxes increased by a factor of ~ 5 . The observed impurity retention behavior on surfaces exposed to the plasma including the effects of sputtering is consistent with the values determined for the impurity and D fluxes, 6) the large flux of iron at the radius of the ring limiter indicates that this is a primary source of metal impurities in PLT.

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FIGURE CAPTIONS:

1. Schematic diagram of the sample holder assembly (b) and the position of the sample holder with respect to the plasma in PLT (a).
2. The measured amounts of impurities (Fe, O, and Ti) determined from RBS analysis versus lateral position along the sample for the carbon strip exposed at $r = 49.1$ cm. Also shown for comparison is the amount of deuterium retained. The slit geometry is illustrated at the top of the figure and the arrows at the bottom indicate the positions on the sample located beneath the slit during the exposures and the corresponding number of discharges. The dotted line shows the profile for effusive flux through a slit aperture.
3. The areal density of impurities retained versus number of discharges for two samples at different distances from the plasma. Note the different vertical scales.
4. The areal density of impurities retained versus distance from the plasma and for exposure to different numbers of discharges. The horizontal axis shows the distance from the sample to the minor axis of PLT. The radius of the ring limiter and wall are indicated. Note the different vertical scales.
5. The areal density of iron retained versus radial distance and number of discharges.

IMPURITIES AND DEUTERIUM RETAINED ON A CARBON PROBE EXPOSED IN PLT

IMPURITIES VERSUS NUMBER OF SHOTS

IMPURITIES RETAINED ON CARBON PROBES EXPOSED IN PLT

IRON IMPURITY IN PLT