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LOW-Z IMPURITIES IN PLT

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ABSTRACT

Low-Z impurities concentrations (oxygen and carbon) have been measured in different discharges in PLT. The contribution to Z_{eff} , influx rates and radiation losses by oxygen and carbon were obtained. An inverse correlation was found between the low-Z impurity density (and also the edge ion temperature) and the high-Z impurity (tungsten) density. A one-dimensional computer transport model has been used to calculate the spatial profiles of different oxygen and carbon ionization states. This model predicts that fully stripped oxygen and carbon ions should exist near the plasma periphery.

INTRODUCTION

Oxygen and carbon, the most abundant low-Z impurities in tokamak discharges, play an ambivalent role. The reason is that in a tokamak discharge, the detrimental effects of the associated radiation loss (e.g., Reference 1 and 2) are often compensated by the beneficial effects of a more favorable electron temperature (and hence current) profile due to the presence of moderate amounts of oxygen. This had already been observed in the ST experiments^{3,4}, and is even more strongly evident in recent PLT experiments, where the strongly radiating oxygen ions near the plasma periphery create an appropriate interface between the hot plasma and the walls and tungsten limiter. Indeed, an inverse relationship was found to exist between the presence of high-Z radiation and low-Z radiation and a correlation between high-Z radiation and the peripheral temperature of the discharge. Nevertheless, since the radiation losses are proportional to electron density, it is unavoidable that a necessary condition for achieving higher density--all else being equal--is a lower impurity concentration.

In the next section, we will present the measurements of oxygen and carbon concentrations and influx rates in a wide variety of PLT discharge conditions: before and after high and low power discharge cleaning (PDC and TDC), in hydrogen, deuterium and helium discharges, with both hollow and peaked electron temperature profiles. In order to understand the relationship between the essentially unobservable fully stripped

oxygen ions to the observable partially stripped ions, a computer model simulating the carbon and oxygen diffusion in PLT plasmas has been used. Preliminary results of this model will be discussed in the section entitled Computer Simulation.

EXPERIMENTS AND RESULTS

The determination of the oxygen and carbon ion densities and influx rates follow the standard method (described in detail, for example, in the TFR report of Reference 5). From measured absolute line intensities and electron densities, and the knowledge of excitation and ionization rates, it is possible to determine the absolute ion density near the beginning of the discharge when the distribution along the line of sight is fairly uniform. During the quasisteady part of the discharge, it is similarly possible to determine the ionization or influx rate of these ions. In some cases, the influx rates are in the same ratio to hydrogen influx rates as the early densities were to proton densities, leading to the conclusion that the relative oxygen concentrations remain constant in time. This was practically always the case in ST and ATC discharges but not in PLT. In PLT, the quasisteady influx rate often indicates a higher proportion of oxygen than the early composition. Thus, as will be discussed further, the concentration of low-Z impurities during the quasisteady state may be uncertain because the transport model for the impurities is still not well known.

The radiated power was determined from measured absolute intensities of a few of the strongest lines and estimates of

the fairly well-known relative intensities of other, unobserved lines.

The line intensities were measured with a grazing incidence vacuum monochromator,⁶ a 1-meter Ebert-Fastie monochromator equipped for the visible and Schumann region,⁷ and three 0.5-meter Ebert-Fastie monochromators in air, located with respect to PLT as shown in Figure 1. All these monochromators were calibrated for absolute intensity measurements. The time of the peak intensity of the various oxygen and carbon lines, as well as hydrogen and helium lines from a typical (not hollow) PLT discharge are shown in Figure 2, together with line-averaged electron densities and central (peak) electron temperatures.

Table I gives the results of the oxygen and carbon concentrations under different discharge conditions, as well as the effective ion charge (Z_{eff}). The discharges in columns marked (PDC) were produced after high-power discharge cleaning of the vacuum vessel, and were characterized by centrally peaked $T_e(r)$ profiles. (High power discharge cleaning consisted typically of ~ 70 kA pulses of ~ 50 msec duration every 15 secs, with $B_T \approx 8$ k gauss.) Those discharges produced after the more effective Taylor discharge cleaning (TDC) method had in the quasi-steady state hollow profiles. (TDC, as employed on PLT, consisted of a series of ~ 8 kA pulses of 10-40 msec duration at a rate of 1 pulse/sec with $B_T \approx 1-7$ k gauss.)

The Z_{eff} values on Table I were deduced from measured oxygen and carbon concentrations only, without including other

impurities after allotting the remaining electrons to hydrogen (or helium as appropriate). The corresponding Z_{eff} values determined from $T_e(r)$ profiles and plasma resistance showed considerable pulse-to-pulse variations, with mean values generally somewhat higher than those deduced from plasma composition, particularly for low oxygen content.

Correlations of low-Z and high-Z impurities with the plasma edge temperature are shown in Figure 3. In this case, the deuterium gas-injection programming was used to change the discharge from hollow to peaked $T_e(r)$ profiles. The ion edge temperature was measured from Doppler broadening of the λ 1548 Å C IV line, which is emitted at radii within a few centimeters inside the limiter radius. As the discharge changes from hollow to peaked $T_e(r)$ profiles, the edge ion temperature drops, the light impurity concentrations increase, and the tungsten concentration (as seen from the drop of the intensity of the 50 Å radiation intensity per electron) decreases. Evidently, the increased peripheral oxygen radiation and deuterium ionization rate lower the edge temperature and conductivity, forcing the current and power input distribution inward to produce the peaked temperature profile. Concurrently, the lower edge temperature appears to reduce the tungsten influx rate and hence tungsten concentration and central radiation losses, thus further facilitating the central temperature rise. Similar changes in temperature profiles, etc., have been induced by injecting small

(~ 1%) quantities of neon, without changes in the deuterium injection rate.

Table II gives typical results of power radiated by the oxygen and carbon ions. (Power radiation losses from balometers measurements are described in Ref. 8.) Near the beginning of the discharge when all the ions are in the strongly radiating lower stages of ionization, the radiation level is high, comparable to the power input (typically for discharges after PDC). In the quasisteady state, however, where a large fraction of the plasma volume contains relatively weakly radiating ions, the radiated power has dropped by a factor 2-6. It is then a rather small fraction of total power input, although it is important locally near the periphery of the plasma.

Time behavior of the ion influx rate and the total radiated power for three different discharges are shown in Figures 4, 5, and 6. Figure 4 describes a deuterium discharge of rather low density and a hollow $T_e(r)$ profile (also described in References 9 and 10). The power input is slightly over 1 MW, and a large fraction of it is radiated by tungsten ions. The tungsten radiation shown in the figure is only that of the 30-70 Å region¹¹ and constitutes an unknown (albeit a fairly large) fraction of the total. The oxygen influx rate follows roughly the electron density and probably also the deuterium influx rate although the latter was not determined on this discharge.

Figure 5 depicts the behavior of a high-density helium discharge (also in Reference 12), achieved by continuous influx

of helium. Here the absolute oxygen influx rate is not too different from the preceding case, but it falls rather than rises with the helium influx and increasing density. Power input was about 0.6 MW at 200 msec, and .85 MW at 700 msec. Thus radiation is again a considerable fraction of power input, but here it is largely helium radiation from the periphery of the discharge. In both Figures 5 and 6, the helium influx was measured at only one location by the grazing incidence spectrometer. Unlike the higher ionization states of oxygen and carbon which would tend to be relatively uniform over a flux surface, helium radiation may be assymetric and the assumption of toroidal and poloidal symmetry used in our calculation may not be adequate. Thus, there is some uncertainty (a factor of 2 or so) in both the helium influx rate and the power radiated. Tungsten radiation in this discharge was quite small and difficult to measure, and should have had only a very minor effect on the power balance.

A case with slower helium input rate, hence lower density, is shown in Figure 6. The vertical bars indicate pulse-to-pulse variation. (This discharge may also contain a significant amount of deuterium, $N_D/N_e \lesssim 0.1$, as D_2 was added every third pulse in an attempt to achieve a high D_2 -density plasma). Again the absolute oxygen influx rate (and radiated power) is similar to the preceding cases, but its time behavior reflects the change of the time behavior of the helium influx. Tungsten radiation was also noticeable but probably not large compared to oxygen

and helium: about 80 kW in the 30-70 Å bands, and fairly constant from 300-800 msec.

It is clear from even this limited selection of samples that PLT discharges present a large variety of conditions. In some cases, tungsten radiation from the interior appears to be overwhelmingly important. In these cases density, temperature, and confinement times are always small. The confinement time may be improved either by raising the density with appropriate gas injection, or by raising the temperature by allowing the oxygen level to rise (or by adding small amounts of neon). In both cases, tungsten radiation drops--evidently as a result of lower edge temperature.

COMPUTER SIMULATION

The computer simulation program for the low-Z impurity diffusion is similar to the one used for ATC.¹³ The equations describing the j-th state of ionization of oxygen or carbon are given as:

$$\frac{\partial N_j}{\partial t} = - \frac{1}{r} \frac{\partial}{\partial r} r \Gamma_j^{PS} + D_A \frac{\partial N_j}{\partial r} \quad (\text{Diffusion})$$

$$+ N_e N_{j-1} S_{j-1} - N_e N_j S_j \quad (\text{Ionization}) \quad (1)$$

$$+ N_e N_{j+1} \gamma_{j+1} - N_e N_j \gamma_j \quad (\text{Recombination})$$

where

$$\gamma_j = \alpha_j + \delta_j + N_e \beta_j$$

Γ_j^{PS} is the flux of the j -th ion species due to Pfirsch-Schlüter diffusion,¹⁴ D_A is an adjustable diffusion coefficient that will give steady-state solutions with finite particle confinement time, S_j is the ionization coefficient,¹⁵ and α_j , δ_j , and β_j are radiative,¹⁶ dielectronic,^{17,18} and three-body recombination coefficients from the j -th state. The electron densities, and electron and ion temperatures required for the coefficients, are taken from the experiment. The set of simultaneous equations, together with the condition of charge neutrality, are then solved for the ion densities $N_j(r,t)$. A typical sample of the results is shown in Figure 7 for a helium plasma. The results in hydrogen or deuterium are quite similar to this, since they depend primarily on the electron temperature distribution. The most interesting feature of these distributions is the spreading of the fully stripped (hence experimentally unobserved) O^{8+} to large r , due to the relatively slow process of recombination. The presence of the fully stripped O^{8+} ions in the periphery is insensitive to the transport model used and to variation in ionization and recombination rates. This feature of the calculations was noted previously.¹³ It is important to test this result experimentally, since it may affect noticeably the calculation of the mean ion charge and expected plasma resistivity.

One other result of this model is that the ratio of the volume averaged density of the fully ionized species to the lower stages of ionization is strongly diffusion model dependent.

Thus, as mentioned above, it is difficult to interpret the evaluation of the low-Z impurities in the quasisteady phase of the discharge from measurements of influx rates.

CONCLUSION

Oxygen and carbon concentrations and influx rates have been determined on a large variety of PLT discharges. Oxygen is typically present in quantities of several percent of hydrogen (or helium), but the amount may vary by factors of about 3-6 depending on previous history (e.g., manner and length of discharge cleaning) and also on the manner of gas injection during the discharge. Carbon is usually present in much smaller quantities than oxygen except for helium discharges. As in most tokamaks, oxygen appears to dominate the behavior of plasma resistivity, both by determining the effective ion charge, and by changing the radial temperature profile through peripheral radiation cooling.

The edge temperature also appears to be the crucial factor in determining the tungsten influx rate, leading to a reciprocal relationship between oxygen and tungsten, or low-Z and high-Z impurities in the discharge. This phenomenon has been observed in earlier tokamaks, but its effects are more pronounced in PLT, because of the somewhat lower power input densities. Since tungsten radiation affects strongly the central radiation intensity and hence temperature and power input (if the radiated power is a significant fraction of local power input), it follows that fairly small changes in oxygen concentration can strongly

influence the plasma behavior, e.g., by changing a centrally peaked electron temperature distribution into a hollow one.

The strong interdependence of the various plasma parameters, particularly the effect of plasma composition (e.g., oxygen vs. tungsten) on the current density distribution, combined with the extraordinarily complicated wall interactions (sorption, chemical reactions, sputtering, unipolar arcs) will continue to render the oxygen problem in tokamak discharges unpredictable even though it is relatively well understood in principle.

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Table I.

Oxygen and carbon density and $\bar{Z}_{\text{eff}}$ for different discharges.

Gas		Helium	Deuterium	Hydrogen	Helium	Deuterium
Discharge Cleaning*		PDC	PDC	TDC	TDC	TDC
Date		28,29 Sept 76	5 Oct 76	10,11 Feb 77	2 Mar 77	4 May 77
Oxygen	N_{O} (10^{11} cm^{-3})	3.3	6.0	1.0	0.75	1.0
	$N_{\text{O}}/N_{\text{e}}$ (%)	1.5	7.5	0.5	0.5	1.0
Carbon	N_{C} (10^{10} cm^{-3})	20	6.0	5.3	6.2	0.7
	$N_{\text{C}}/N_{\text{e}}$ (%)	1.8	1.2	0.4	0.4	0.1
$\bar{Z}_{\text{eff}}$		3.2	5.6	1.4	2.3	1.6

* PDC and TDC are high-power and low-power (Taylor) discharge cleaning.

Table II.

Oxygen and carbon radiative power losses.

Gas			Helium	Deuterium	Hydrogen	Deuterium	Helium
Discharge Cleaning*			PDC	PDC	TDC	TDC (2h)	TDC
Date			28,29 Sept 76	5 Oct 77	10,11 Feb 77	2 MAR 77	2 Mar 77
Radiative Power (MW)	Oxygen	t $\approx$ 31 msec (Peak of OVI)	0.6	0.7	0.15	0.18	0.24
		t $\approx$ 200-300 msec (Quasisteady)	0.1	0.2	0.07	0.05	0.06
	Carbon	t $\approx$ 27 msec (Peak of CIV)	0.6	0.25	0.1	0.12	0.2
		t $\approx$ 200-300 msec (Quasisteady)	0.15	0.08	0.03	0.04	0.07

* PDC and TDC are high-power and low-power (Taylor) discharge cleaning.

Fig. 1. Location of monochromators with respect to PLT.

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Fig. 2. The time of peak intensity of various oxygen, carbon, helium, and hydrogen lines.

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Fig. 3a. Correlation between oxygen and carbon concentrations, and ion temperature at the plasma edge $T_{i(\text{edge})}$.

Fig. 3b. Correlation between oxygen and carbon density and tungsten band intensity at 50 Å.

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Fig. 4. Oxygen influx rate and radiated power by oxygen and oxygen + tungsten for deuterium discharge with a hollow T_e profile.

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Fig. 5. Oxygen and helium influx rates and radiated power by helium and helium + oxygen in a high density helium discharge.

773822

Fig. 6. Oxygen and helium influx rates and radiated power by helium and helium + oxygen in a helium + deuterium discharge.

773821

773818
Fig. 7. Computer simulation of the oxygen density as a function of radius.