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HEAVY-IMPURITY RECYCLING AT A
LIMITER AND POWER-LOSS
LIMITATION TO A LIMITER IN
TOKAMAK

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Heavy-Impurity Recycling at a Limiter and
Power-Loss Limitation to a Limiter in Tokamak

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ABSTRACT

Since the density of high- z impurities in tokamaks is generally observed to saturate, the heavy-impurity recycling rate is presumed to be less than unity. On this basis, plasma edge temperature is calculated to be low and an upper limit to power carried out by charged particles is estimated to be small as observed in experiment. This result suggests that the total radiation loss by low- and high- z impurities is always large in a conventional tokamak with high power input and small charge-exchange loss.

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I. INTRODUCTION

The energy balance in steady state of tokamak operation is provided by power input and by heat loss to a limiter and chamber wall and is approximately given by the following equation:

$$P_I = P_{cx} + P_R + P_L \quad (1)$$

where P_I , P_{cx} and P_R are the power input, charge-exchange loss and radiation loss, respectively. P_L is the heat loss, carried by charged particles, which is absorbed by the limiter in the ideal case and is called power loss to a limiter in the following discussion. In the ATC tokamak,¹ the heat loss to the wall was found small by using a bolometer which measured the sum of P_{cx} and P_R . Discharges in PLT² or TFR,^{3,4} however, lose most of their heat not to the limiter but to the wall. One of the distinct differences between the former device and the latter ones is power input: $P_I = 200$ kW in ATC and $P_I = 500-800$ kW in PLT and TFR. This result suggests that $(P_{cx} + P_R)/P_I$ increases and P_L/P_I decreases with increasing P_I . The radiation loss is the main part of the heat loss to the wall because the charge-exchange loss is small in a conventional tokamak at least without neutral beam injection.³ This suggests that radiation loss dominates the energy balance in a tokamak with high power input.

Two kinds of impurities which have been observed are the light elements of absorbed gas on the first wall and heavy

elements originating from the wall material. In DITE tokamak,⁵ high-z impurities have been shown to decrease by a large factor by operating the bundle divertor but the low-z impurities are still dominant as is often observed in the present conventional tokamaks. That light impurities can be essentially eliminated by cleaning the first wall has been shown in experiment.^{6,7} Thus, the question: Is it possible to reduce the high-z impurities after reducing the low-z impurities?

In ST tokamak,⁸ however, the high-z impurities increased when the low-z impurities decreased and in DIVA tokamak,⁹ the heavy impurities dominate the Z_{eff} and radiation loss with a negligible amount of light impurities present. In the latter small tokamak, plasma-wall interaction in a high power tokamak has been simulated by employing gold surfaces which have a high sputtering yield and poor thermal properties and the radiation power-loss from the heavy impurities has been increased up to 90% of the input power by spoiling the divertor. Operating the divertor, the radiation power-loss has been shown to be reduced by a factor of 2 ~ 3,⁹ but is still large. These results suggest that with a negligible amount of light impurities, the reduction of heavy impurities is difficult in a discharge.

The contamination mechanisms have to be clarified to understand the high-z impurity behavior and are as follows:

- 1) Evaporation.
- 2) Sputtering by charge-exchange particles.
- 3) Sputtering by ions.

The first mechanism is not important if energy deposition on a small area can be eliminated. The second process has not been dominant in small or medium size tokamaks,^{9,10} but has been shown to be important with neutral beam injection.⁴ This mechanism may become more important in future large tokamaks with high power injection. Sputtering by a heavy ion itself, self sputtering, is the most important process in the last mechanism because it can increase the high-z impurities including impurities from in the discharge startup. Without recycling, the impurities contaminated in the discharge start-up are lost early in the discharge because the confinement time of impurities has been found to be of the same order as the energy-and particle-confinement time.^{11,12} This mechanism may also explain the experimental result: the power loss to the limiter is a small fraction in high power tokamaks. The relation between the radiation loss and the heat loss to the limiter seems to be governed by a natural feedback mechanism through the self-sputtering as follows. When the heat loss to the limiter is large, the plasma temperature at the edge of a column is high. In order to accommodate power flux, the limiter emits high-z impurities because of the very high self-sputtering yield. These impurities cause the plasma to channel a greater fraction of its power input to radiation, rather than to the limiter and thereby reduce the self-sputtering yield. The plasma edge cools and the density of the high-z impurities saturate as observed in experiment.^{13,14,15} From this point of view, the heavy-impurity recycling and the gross power balance in steady state are discussed in this paper.

In Section II, the high-z impurity recycling and upper limits for the edge temperature and the heat loss to a limiter are discussed. In Section III, examples of the upper limits are shown and compared with experiment. Possible methods to control the recycling are discussed in Section IV.

II. SATURATION OF HEAVY IMPURITIES AND POWER-LOSS LIMITATION TO A LIMITER

The total number of high-z impurities is given by the following equation:

$$\frac{dN_z}{dt} = (R_s - 1) \frac{N_z}{\tau_z} + F_z \quad (2)$$

where N_z , R_s , τ_z and F_z are the total number of high-z impurities, their recycling rate, their confinement time and their influx caused by other particles such as charge-exchange particles, protons and low-z impurities and by evaporation. When $R_s > 1$, N_z increases exponentially and $R_s < 1$ in the steady state. R_s is given by the following equation:

$$R_s = \alpha [S(E_z) + R] \quad (3)$$

where α is the probability of ionization and trapping of heavy atoms by the main plasma, $S(E_z)$ is the sputtering yield by heavy ions with energy of E_z and R is a reflection coefficient. To satisfy $R_s < 1$, E_z has to be low because a high E_z gives a very high sputtering yield. E_z is given by the following equation:

$$E_z \approx zV_s + T_z \quad (4)$$

Where z , V_s and T_z are the charge number, sheath potential and temperature to the heavy ion, respectively. Since V_s and z increase with increasing electron temperature, the electron edge temperature, T_e , has to be low in steady state.

The heat flux to a material surface is carried mainly by electron and is approximately given by the following equation:

$$P_L \approx \gamma T_e F_p \quad (5)$$

where F_p is the particle flux to a limiter and γ is a numerical constant. The particle flux to the limiter coincides with the particle flux because the recombination rate is negligible with $T_e > 10$ eV and F_p is rewritten as follows:

$$F_p \approx \frac{N_e}{\tau_p} \quad (6)$$

where N_e and τ_p are the total number of electrons and the gross particle-confinement time of the main plasma column. P_L is not strongly changed by increasing machine parameters because N_e is proportional to the major radius and square of the minor radius, τ_p is also proportional to the square of the minor radius and T_e is limited as discussed above. The power input, however, is expected to increase strongly with increasing machine parameters.

Thus, the power loss to the limiter is a small fraction of the power input in a future large tokamak which suggests that radiation loss dominates the energy balance if charge-exchange loss is small. The necessary radiation loss is easily obtained as follows. When the radiation-loss and charge-exchange loss are small, P_L has to be large to satisfy the energy balance. P_L is given by Eq. (5) and a large P_L is provided by a high T_e which gives a high energy for E_z because of a high sheath potential and a high ionization level. R_s can easily increase to more than one because of the very high self-sputtering yield with a high E_z . Thus, the high-z impurities and the radiation loss increase while P_L decreases until a value of R_s less than unity is obtained. After realizing this situation, the impurity contamination level does not change without a change of impurity emission by other mechanisms or a change in the plasma parameters. P_L , however, can be smaller than the estimated upper limit which is obtained from Eq. (6) with the estimated maximum electron temperature, when another mechanism of impurity emission, for example, sputtering by charge-exchange particles, is dominant.

III. COMPARISON WITH EXPERIMENT

The estimated power loss to the limiter is compared with experiment for various tokamak discharges in Table I. We employed the following assumptions:

- 1). $R \approx 0$ and $\alpha \geq 0.5$ because at least half of the sputtered atoms flow into the main plasma. Thus, $S(E_z) < 2$.

- 2) $V_{S1} = 3 T_e^{19}$
- 3) Coronal equilibrium and $T_z = T_e$
- 4) $\gamma = 7.8^{20,9}$
- 5) $\tau_p = 0.85 \times 10^{-20} \bar{n}_e a^2$ where $\bar{n}_e$ is the mean electron density in the main plasma column in m^{-3} and a is the minor radius in m.²¹

The measured power loss to the limiter is smaller than the estimated value in all tokamaks. The measured electron temperature at the edge is also consistent with the estimated value in DIVA.⁷ The following behavior of impurities observed in experiment is also explained by the above discussion. The high-z impurities decrease with increasing low-z impurities^{3,8} and increase with decreasing low-z impurities⁸ because the self-sputtering yield is reduced as the light-impurity radiation cools the edge-plasma and vice versa. Z_{eff} is reduced by increasing the plasma density²⁴ because the radiation loss increases with increasing Z_{eff} and the density for the same kinds of impurities and constant electron temperature.

The idea of the power loss limitation to a limiter in the steady state seems correct over a wide range of power input, 55 ~ 800 kW.

It should be pointed out that the power loss to a graphite limiter increases up to 320 kW in TFR.⁴ This result is consistent with the small estimated self-sputtering yield for graphite.¹⁸ In T-10, an alloy of molybdenum and tungsten is employed as the limiter and a rather small fraction, ~ 50%, is emitted to the wall with a high input power, 800 kW.¹⁵

IV. DISCUSSIONS

The maximum heat flux to a limiter is limited by the saturation condition of the high-z impurity and is estimated to be small, which suggests that the rest of the input power has to be radiated to the wall. The above estimation is rather semiquantative because of many assumptions such as $R_s = 0.5$, coronal equilibrium, the normal sheath, the particle confinement time, and so on. The power balance estimate does not change much at least with assumptions of $\tau_n \propto a^2$ and a normal sheath and suggest a serious radiation loss in a high power tokamak. This problem is not changed by employing a divertor in which sputtered atoms from a neutralizer plate are easily ionized in a shielding scrape-off layer and the impurity influx from the divertor becomes important.⁹ Heavy impurities radiate energy from a hot column and shorten the energy-confinement time.²⁴ Some methods to mitigate the high-z impurity problem are discussed.

The gross power balance is given by Eq. (1). If we can increase $1/P_I$, P_{CX} , P_R and/or P_L without serious adverse effects to the main plasma, the problem can be solved. P_I can be reduced by improving the plasma confinement. A gas blanket has the possibility of enhancing P_{CX} near the edge of the plasma column without adverse effects to the main plasma column. The temperature at the edge can be kept around 10 eV in a EPR size tokamak if a constant density profile with density of 10^{14} cm^{-3} can be obtained.²⁵ Some low-z impurities may enhance P_R also only

near the plasma edge since a permissible level of gaseous impurities has been shown to cool the edge plasma to a low temperature in a high density reactor.²⁶ The last term of the Eq. (1) is given by Eq. (5) and increases with γ , T_e and F_p . In the normal sheath γ is about 7.8 and increases with electron emission from a limiter or a neutralizer plate.¹⁹ The secondary electron emission may increase γ by a factor of about 2 (one electron emission by each ion¹⁹) and the thermal electron emission from a hot plate can also increase γ by a large factor.¹⁹ The hot plate, however, may evaporate the metallic impurity. A high energy electron component increases γ .⁹ If we can disconnect the sheath potential from the electron temperature, the maximum electron temperature can be increased without increasing the sputtering. One possible method of decreasing the sheath potential is by electron emission and another is to obtain a low temperature plasma at the neutralizer plate by having a large ratio of the electron heat conduction length to the magnetic field line length. The latter possibility is discussed in Ref. 27. The last term, F_p , can be increased by having a low temperature plasma source in the scrape-off layer²⁸ or a thick scrape-off layer to ionize the reflected hydrogen from the neutralizer plate.

Another scheme to mitigate the problem is reducing R_s , given by Eq. (3). α can be decreased by employing a suitable shape²⁹ for the limiter or the neutralizer plate, but the problem of wall erosion cannot be eliminated by this method. The sputtering yield decreases with small E_z which can be realized by reducing the sheath potential. If we can find

some suitable material with a self-sputtering yield much less than 2, the power loss to the limiter can be increased.

The last scheme is active removal of the impurity. The problem of the erosion, however, cannot be eliminated by this method either.

The conclusions of this paper are summarized as follows.

1. Considering acceleration of the multi-charged heavy ions by the sheath potential at a limiter surface, self-sputtering is one of dominant mechanisms of high-z impurity contamination not only in a future large tokamak but also in the present tokamaks.

2. The steady state tokamak is only obtained with a heavy impurity-recycling rate of less than one which is provided only by a low temperature, typically 60 eV or less, edge plasma. This low temperature plasma provides a small power loss to the limiter which is estimated and consistent with experiment.

3. High-z impurity contamination by self-sputtering and radiation loss become much more serious in future large tokamaks and possible methods to mitigate these problems are reviewed.

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TABLE I. Power Loss to Limiter

	Limiter material	E_z for $S=2$ (keV)	Estimation		Experiment			
			Max, edge temperature T_e (eV)	Max. power to limiter P_L (kw)	Edge temperature T_e (eV)	Power to limiter P_L (kw)	Input power P_I (kw)	Ref.
DIVA	Au	$\sim 0.3^{16}$	~ 20	~ 35	20	33*	55	7
					-	22 ⁺	55	9
					-	10 ⁺	76	9
					-	17 ⁺	72	9
					-	28 ⁺	126	9
ST	Mo	$\sim 1.5^{17}$	~ 60	~ 180	-	100-150 ⁺	125-175	22
ATC	Mo	~ 1.5	~ 60	~ 160	-	140*	200	1
ORMAK	W	$\sim 1.5^{18}$	~ 60	~ 140	-	120-170*	480	23
TFR	Mo	~ 1.5	~ 60	~ 160	-	145*	520	23
						50-140*	440	4
PLT	W	~ 1.5	~ 60	~ 210	-	30	500	2
						80	800	2

$$* P_L = P_I - P_{cx} - P_R$$

$$+ P_L = P_I - P_R$$

where P_{cx} and P_R are measured charge-exchange loss and radiation loss, respectively.

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