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A STUDY ON IMPURITIES AND SCRAPE-OFF LAYER PLASMA IN A LARGE TOKAMAK

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A Study on Impurities and Scrape-off Layer Plasma in a Large Tokamak

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The scrape-off layer is studied by using a simple model which gives a low temperature at the edge of a plasma column in the present tokamaks. In a future large tokamak, the scrape-off layer has to be controlled to eliminate the serious impurity contamination from a neutralizer plate (or a limiter) and vacuum walls. One of the suitable scrape-off layers is shown to be cold and thick. Possible methods to obtain this scrape-off layer are also discussed.

大型トカマクにおける不純物およびスクレイプ・オフ層に関する考察

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簡単なモデルによって，スクレイプ・オフ層の考察をおこない，つぎのような結論を得た。このモデルでは，現在のトカマクのスクレイプ・オフ層の温度として，低い値を与える。将来の大型トカマクにおいては，中性化板（またはリミタ）および壁からの不純物混入をふせぐために，スクレイプ・オフ層の制御が必要であり，低温で厚いスクレイプ・オフ層が適している。またこのようなスクレイプ・オフ・プラズマを得る方法についての考察もおこなった。

Contents

1. Introduction

To eliminate the serious effects of impurities, some active controls of impurity contamination have to be necessary in a large device. Two kinds of impurities, which are the impurity of the absorbed gas on the wall surface and the impurity of the wall material, have been observed in many tokamaks. The impurity of the absorbed gas on the surface, however, can be essentially eliminated by cleaning the wall surfaces.1)-3) For this reason, the impurity from the wall material is essential problems in a large machine and is discussed in this note.

The mechanisms of the impurity contamination from the wall material are as follow.

A) Sputtering by cx particles from the first wall.

B) Sputtering by the edge plasma particles from a limiter or a neutralizer plate.

C) Evaporation.

The last mechanism depends on how much energy concentrates on a small area and can be eliminated by careful control of a plasma and use of a suitable limiter or a neutralizer plate. The other mechanisms are discussed in more detail.

To reduce the impurity contamination by cx particles, the following methods are useful.

A-1) Reducing cx particles by reducing neutral particles.

A-2) Reducing energy of cx particles by reducing the temperature near the edge of the plasma column.

A-3) Shielding the impurity influx and sweeping the ionized particles to a divertor.

To realize the first scheme an extremely fast pumping such as a non loading divertor is necessary, and controlling desorption from the wall and fueling without producing neutral particles are also necessary. To realize the second scheme, the plasma near the edge has to be kept cold and dense to eliminate a high energy cx particles. The ion temperature T_{HE} near the edge has to be less than the threshold energy of the sputtering, typically 100 eV or less,4) and the line density $n_{eE}d_E$ of the cold plasma has to be much higher than $v_H / \langle\sigma v\rangle_{Hi}$ where v_H is the velocity of a neutral with T_{HE} perpendicular to the plasma column and $\langle\sigma v\rangle_{Hi}$ is a ionization rate. To realize the last scheme, the line density $n_{eS}d_S$ in a scrape-off layer has to be much larger than v_i $/<\sigma v>_{ii}$ where v_i is the impurity velocity perpendicular to the scrape-off layer and $<\sigma v>_{ii}$ is an inonization rate, and the thickness d_S of the scrape-off layer has to be much larger than the diffusion distance d_{Di} of the ionized impurities during the time in which the impurities are swept into a divertor. The above discussions are summerized in Table 1.

To reduce the impurity contamination from a limiter or a neutralizer plate, the following methods are considered.

B-1) Reducing sputtering by reducing the energy of ions flowing into the limiter or the neutralizer plate.

B-2) Reducing impurity back flow from a divertor by eliminating ionization by a scrape-off layer.

B-3) Reducing impurity ion back flow from a divertor by a density gradient and/or statistic potential.

To realize the first scheme, the energy of a hydrogen ion E_H and the energy of an impurity E_{zi} flowing into the limiter or the neutralizer plate have to be less than the threshold energy of the sputtering, typically 100 eV or less, and the energy which gives the unit for the sputtering ratio, typically 500 eV,4) respectively. These energies are roughly given by the following equations.

$$E_H = T_{HS} + V_S \text{ and } E_{zi} = T_{is} + zV_s,$$

where T_{HS}, T_{iS}, z and V_S are hydrogen ion temperature, impurity ion temperature, ionization level of the impurity and sheath potential. With a normal sheath $V_s = 3xT_{eS}$5)6) where T_{eS} is the electron temperature. Then the typical temperature is around 30 eV or less if we assume $T_{iS}=T_{HS}=T_{eS}$, Mo impurities and coronal equilibrium.* Without any sheath potential, the typical temperature is around 100 eV or less. To realize the second scheme, a thin scrape-off layer is necessary. When the last scheme is valid, the impurity contamination level near the neutralizer plate is permitted to be large. The impurity buildup, however, has to be eliminated and the conditions may be similar to those of the scheme B-1). The above discussions are also summarized in Table 1.

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* If we assume 50% of sputtered impurities go to the wall without ionization, $T_{es} \leq 60$ eV. If we assume non coronal equilibrium, the permissible temperature of T_{es} increases.

To obtain a pure plasma, one scheme of the first three (A-1, A-2 and A-3) and one scheme of the following three (B-1, B-2 and B-3) have to be realized. The set of A-3 and B-2 are inconsistent with each other, and the erosion of the neutralizer plate cannot be eliminated by employing the scheme B-2). The scheme A-1) does not seem realistic if the large neutral beam injectors are necessary. For these reason, the simplest solution seems a cold shielding plasma in a scrape-off layer (A-3 and B-1). In this case, a divertor is not essentially necessary but it seems suitable for the easy control of the scrape-off layer plasma. The scheme B-3 may mitigate the conditions of the scheme B-1. In the following sections, the scrape-off layer is discussed by using a simple model and some possible methods to realize the cold shielding plasma layer are also discussed.

Table 1. Impurity contamination and its suppression

Contamination Mechanisms	Suppression Methods
A) Sputtering by cx particles from wall	<u>A-1) Reducing neutral particles.</u> Fast pumping such as non loading divertor. Fueling without producing neutral particles. Controlling of absorption and/or desorption. <u>A-2) Reducing energy of cx particles.</u> Cold and dense plasma near the edge of a column. $T_{HE}<100$ eV and $n_{eE}d_E >> v_H / <\sigma v>_{Hi}$ <u>A-3) Shielding impurity influx.</u> Thick scrape-off layer. $n_{eS}d_S >> v_i / <\sigma v>_{ii}$ Wide scrape-off layer. $d_S > d_{Di}$
B) Sputtering by ions from limiter or neutralizer plate	<u>B-1) Cold scrape-off layer.</u> $T_S \leq 30 \sim 50$eV with normal shieth. $T_S \lesssim 100$eV without any shieth potential. <u>B-2) Non shielding divertor.</u> Thin scrape-off layer. $n_{es}d_s << v_i / <\sigma v>_{ii}$ <u>B-3) Suppression of back flow from a divertor.</u> (The conditions are similar to those of B-1.) Density gradient or potential.

2. A Simple Formulation of a Scrape-off Layer

The following equations are assumed as the conservations of particles and energy.

$$\bar{n}_e Sa/2\tau_p = s\,\frac{n_{es}Sd_s}{\tau_{\parallel}} \qquad (1)$$

$$\alpha P_{input} = P_{cs} + P_{RS} + P_{iS} \qquad (2)$$

where

$\bar{n}_e$: mean density of a main plasma column.

n_{es}: density of a scrape-off layer at the boundary.

S : surface area of a plasma column.

a : minor radius.

d_S : thickness of a scrape-off layer.

τ_p : mean particle-confinement time.

$\tau_{\parallel}$: mean particle-confinement time of a scrape-off layer.

(1-s): effective recycling rate in a scrape-off layer.

P_{input}: total energy input.

$(1-\alpha)P_{input}$: energy loss by radiation and cx from a main plasma column.

P_{cs}: energy flux to a limiter or a neutralizer plate.

P_{RS}: radiation loss from a scrape-off layer plasma.

P_{iS}: ionization loss in a scrape-off layer plasma.

We assume $\bar{T}_e=\bar{T}_H=\bar{T}$ in a main plasma column and $\bar{T}_{eS}=\bar{T}_{HS}=\bar{T}_S$ in a scrape-off layer. The left side of the equation 2 is written as follows.

$$\alpha P_{input} = 3\alpha\bar{n}_e\bar{T}Sa/2\tau_E \qquad (3)$$

where τ_E is the energy-confinement time. The each term of the right side is written by the following equations.

$$P_c = \gamma n_{es}Sd_S\bar{T}_S/\tau_{\parallel} \qquad (4)$$

$$P_i = \gamma_i n_{es}Sd_S\Sigma P_z/\tau_{\parallel} \qquad (5)$$

$$P_R = \gamma_i\bar{n}_{es}^2 Sd_S\delta_i R(Te)\ell \qquad (6)$$

where γ is the ratio of the heat flux to the particle flux times electron temperature, and γ_i, ΣP_z, $d_S S\delta_i\ell$, $R(T_e)$ and ℓ are the fraction of impurity, ionization potential, effective volume where impurities are concentrated, radiation loss normalized by volume, and number of limiters or neutralizer plates, respectively. We assumed that the impurity flow velocity is same as that of the field particles. From equations (1 - 6), we obtain the following relation between the temperature in a scrape-off layer and the temperature of a main plasma column.

$$\frac{\bar{T}}{\bar{T}_s}\left(\frac{3\alpha s}{\gamma}\,\frac{\tau_p}{\tau_E}\right) = 1 + \frac{\gamma_i}{\gamma T_s}\left(\Sigma P_z + \frac{\bar{n}_{es}^2}{n_{es}}\,\tau_{\parallel}\;\delta_i R(T_e)\right) \qquad (7)$$

The parameters of τ_{11} and d_S are given by the following equations.

$$\tau_{\parallel} = L/v_f \qquad (8)$$

$$d_S = \sqrt{\tau_{11} D_{\perp}/s} \qquad (9)$$

where L, v_f and $D_{\perp}$ are the mean length of the magnetic field lines in a scrape-off layer, particle flow velocity and diffusion constant. We assume the following equations.

$$v_f = \frac{1}{4}\sqrt{\frac{8}{\pi}\,\frac{kT}{m_H}} = 4 \times 10^3 \sqrt{\bar{T}_S(\mathrm{eV})} \quad \mathrm{m/sec} \qquad (10)$$

$$D_{\perp} \equiv 0.1\, D_B = 6.25 \times 10^{-3}\; T_e/B_T \;\mathrm{m^2/sec} \qquad (11)$$

$R(T_e)$: Calculated values assuming coronal equilibrium. $L=\pi Rm$, where $m=q/\ell$ for a tokamak with a separatrix magnetic surface with ℓ's neutral points, $m=\pi\sqrt{a/2d_S}$ for a conventional tokamak with a rail limiter, and m=1 with an ideal poloidal limiter.

In a normal tokamak, s=1, $\tau_P \sim \tau_E$ and the second terms seems small and we assume a normal sheath on the limiter surface (γ=7.8).$^{(6)}$ Equation 7) is simplified as follows.

$$\bar{T}/\bar{T}_S = 2.6/\alpha \qquad (12)$$

Estimated values from this equation are listed in Table 2 for various machines. The estimated $\bar{T}_S$ is consistent with the measured value and is rather low in the small machine (DIVA). $\bar{T}_S$ is rather high and has roughly the same value (46 - 68 eV) in the other machines. (Unfortunately, the temperature near the edge of the plasma column was not measured in these machines.) This value seems equal to the critical temperature above which the impurity buildup occurs if we consider the ionization level is smaller than the value given by the coronal equilibrium and some fraction of the sputtered impurities go to the wall without ionization. One possible explanation for $\bar{T}_S$ = 50eV in various machines is a kind of self-adjusting mechanism. If the temperature is higher than 50 eV, the limiter emits impurities that cause the radiation loss and avoid the impurity buildup by reducing $\bar{T}_S$ down to 50 eV. The radiation loss, however, serious in a rather large tokamaks such as TFR and PLT and some methods are necessary to obtain a cold scrape-off layer without serious effects to the plasma confinement. This problem is discussed in 3 and the shielding problem is also discussed in 4.

Table 2. Plasma Parameters in Scrape-off Layer in the Present Tokamaks

	R (m)	a (m)	B_T (T)	$\bar{n}_e$ ($10^{19}m^{-3}$)	$\bar{T}$ (keV)	$\tau_E=\tau_n$ (s)	α	m**	$\bar{T}_s$ (eV)	$d_s n_{es}$ ($10^{17}m^{-2}$) [d_s(cm)]	$\tau_\parallel$ (ms)
PLT(7)	1.2	0.4	3.5	3.5	0.8	0.04	0.15	25∿1	46	1.9∿0.25 [1.7∿0.25]	3.4∿0.14
TFR(8)	0.98	0.2	6	4.5	0.6	0.017	0.3	21∿1	68	1.8∿0.25 [1.1∿0.4]	2.1∿0.1
JFT-2(9)	0.9	0.25	1.8	1.0	0.3	0.009	0.5	18∿1	57	0.8∿0.13 [1.9∿0.5]	1.8∿0.1
ATC(10)	0.9	0.15	1.5	2.0	0.3	0.005	0.5	16∿1	57	1.5∿0.3 [1.9∿0.6]	1.5∿0.1
DIVA(2)	0.6	0.1	1	1.0	0.1	0.001	0.6	10	24 20∿30*	3(0.27) [1.0 (0.3)]	1.0(0.04)

* measured value.

** assuming a rail limiter and an ideal poloidal limiter in conventional tokamaks.

( ) corrected value for effect of wall.

3. Some Possible Methods to Obtain a Cold Scrape-off Layer

From equation (7), it is possible to obtain a cold scrape-off layer by increasing the parameters, $1/\gamma$, γ, $1/s$, $\gamma_i(\Sigma P_z + \bar{n}_{es}^2 \tau_1\ \delta_i R(T_e)/n_{es})$. The problem is whether some of these parameters can be increased without any serious effects to the plasma confinement or not. In the following subsections, each of these four terms and its control are discussed for two tokamaks whose parameters are assumed as shown in Table 3.

3.1 Parameter α

α is the ratio of the energy flow by conduction and convection to the total energy loss and is decreased by increasing cx loss and/or radiation loss. To avoid the serious effect to the plasma confinement, these losses should be concentrated near the edge of the plasma column. The cooling effect by cx near the edge is discussed in ref. 11 as a cold gas branket and it is shown that the edge plasma can be cooled down to around 10 eV if the density profile can be maintained flat in a EPR size tokamak with a density of $10^{20}\mathrm{m}^{-3}$. In this subsection the radiation loss effects are discussed.

C, O and Ne are considered. The ratio of cooling effect P_T for these impurities are calculated from ref. (12) with the same density and the same contamination level, where $P_T = \int_{5\mathrm{eV}}^{1\mathrm{keV}} P_R dT$ and P_R is radiation loss.

$$P_T(c) : P_T(o) : P_T(\mathrm{Ne}) \approx 0.35 : 1 : 2 \tag{13}$$

To obtain the same cooling effect, each contamination level γ has to satisfy the following equation, because the cooling effect is proportional to P_T.(13)

$$\gamma(c) : \gamma(o) : \gamma(\mathrm{Ne}) \approx \frac{1}{0.35} : 1 : 1/2 \tag{14}$$

The contamination level decreases largely as the atomic number of impurities increases. An adverse effect of impurities is the radiation loss from the main plasma which is given by the Bremsstrahlung loss P in this case.

$$P \approx (1 + Z(Z-1)\frac{\gamma}{100})\ f(n_e,T_e) \tag{15}$$

The other adverse effect is the reduction of fusion power F which is given by the following equation.

$$F \approx (1 - \frac{Z\gamma}{100})^2\ \ g(n_e,T_e) \tag{16}$$

Table 3 Reference Tokamaks

A: $\begin{pmatrix} R=1.5m, \ a=0.5m, \ B_T=2.5T, \ V=7.3m^3 \\ q=3.5, \ I_p=0.5MA, \ m=3, \ \alpha_o=0.7, \ S=30m^2 \end{pmatrix}$

	Main plasma				Scrape-off Layer $\begin{pmatrix}\alpha=\alpha_o, \ s=1 \\ \gamma=7.8, \ \gamma_i=0\end{pmatrix}$			Assuming $\bar{T}_s=20$ eV $\sqrt{sd_s=0.65cm}$		Edge cooling by Ne $\alpha=\alpha_o-\Delta\alpha$ (assuming $\bar{n}_{eE}=0.5\bar{n}_e$)				** Edge cooling by electron emission $\bar{T}_s=100$ eV $d_s=1$ cm			Cold plasma Source $\bar{T}_s=20$ eV	
	$\bar{n}_e$ $(10^{19}m^{-3})$	P_{input} (MW)	τ (s)	$\bar{T}$ (keV)	$\bar{T}_s$ (eV)	d_sn_{es} $(10^{17}m^{-2})$ $(d_s cm)$	$\tau_{\parallel}$ (ms)	$\frac{\alpha s}{\gamma}$	sd_sn_{es}	γ_{Ne}(%) (Z_{eff})	$+\Delta\alpha$	$\bar{T}_s$	P_{BR} (MW)	I_M (KA)	T_M (°K)	$\frac{F_M}{(\frac{\bar{nv}}{\tau_{\parallel}})}$	s	F_P $(10^{22}/s)$
Emperical Plasma $\tau=0.1\bar{n}a^2$ $\bar{T}R=P_{input}$ $K_{eff}=4\times10^{19}m^{-1}s^{-1}$	3	1.5	0.075	1.0	270	0.21 (1.2)	0.21	0.007	0.77	2.5 (3.3)	0.34	140	0.04	1.2	2450	3×10^{-6}	0.074	4.0
		5		3.3	900	0.12 (1.7)	0.12	0.002	0.77	2.5 (3.3)	0.1	770	0.07	4.0	2550	1.5×10^{-5}	0.022	14.
	10	1.5	0.25	1.0	270	0.21 (1.2)	0.21	0.007	0.77	0.8 (1.7)	0.65	20	0.1	1.2	2450	3×10^{-6}	0.074	4.0
		5		3.3	900	0.12 (1.7)	0.12	0.002	0.77	2.5 (3.3)	0.34	460	0.7	4.0	2550	1.5×10^{-5}	0.022	14.
Bohm Plasma $\tau=0.2a^2B_T/\bar{T}$ $R\bar{T}^2\bar{n}/B_T=2\ P_{input}$ $K_{eff}=2\bar{n}\bar{T}/B_T$ $(D_\perp\sim30D_B)$	3	1.5	0.1	1.3	350	0.14 (1.3)	0.19	0.005	0.60	2.5 (3.3)	0.3	200	0.04	1.2	2450	3×10^{-6}	0.060	4.0
		5	0.068	2.4	650	0.15 (1.6)	0.14	0.003	0.85	2.5 (3.3)	0.12	530	0.06	3.3	2550	1.5×10^{-5}	0.031	14.
	10	1.5	0.18	0.71	190	0.36 (1.1)	0.26	0.01	1.1	0.55 (1.5)	0.63	20	0.07	3.7	2550	4×10^{-6}	0.10	4.0
		5	0.12	1.3	350	0.4 (1.3)	0.19	0.005	1.7	2.5 (3.3)	0.54	70	0.45	10.	2650	7×10^{-6}	0.060	14.

$\bar{n}=\bar{n}_e/10^{19}$

$\bar{T}$(keV)

P_{input} (MW)

$P_{BR}=5\times10^{-5}\bar{n}^2<z^2>\ \bar{T}\ V$ M watts

**
$J=120\ T_M^2\ e^{-e\phi/kT_M}$ cm^{-2}
$e\phi=4.5$ eV
W-plate

B: JT-60 $\left(\begin{array}{l} R=3\text{m},\ a=1\text{m},\ B_T=5\text{T},\ V=60\text{m}^3 \\ q=3.5,\ I_p=2.4\text{MA},\ m=6,\ \alpha_o=0.7,\ S=120\text{m}^2 \end{array}\right)$

	Main Plasma				Scrape-off Layer $\left(\begin{array}{l}\alpha=\alpha_o,\ s=1\\ \gamma=7.8,\ \gamma_i=0\end{array}\right)$			Assuming $\bar{T}_s=20$ eV $\sqrt{sd_s}=0.9$cm		Edge cooling by N_e $\alpha=\alpha_o-\Delta\alpha$ (assuming $\bar{n}_{eE}=0.5\bar{n}_e$)				Edge cooling by electron emission $\bar{T}_s=100$ eV $d_s=1.4$ cm			Cold plasma Source $\bar{T}_s=20$ eV	
	$\bar{n}_e$ (10^{19}m^{-3})	P_{input} (MW)	τ (s)	$\bar{T}$ (keV)	$\bar{T}_s$ (eV)	d_sn_{es} (10^{17}m^{-2}) $(d_s\text{cm})$	$\tau_\parallel$ (ms)	$\frac{\alpha s}{\gamma}$	sd_sn_{es}	$\gamma_{Ne}(\%)$ (Zeff)	$+\Delta\alpha$	$\bar{T}_s$	P_{BR} (MW)	I_M (KA)	T_M (°K)	$\frac{F_M}{(\frac{\bar{n}V}{\tau_\parallel})}$	s	F_P $(10^{22}/\text{s})$
Emperical Plasma	3	5	0.3	1.7	460	0.33 (2)	0.66	0.004	1.6	2.5 (3.3)	0.4	200	0.39	18	2650	2×10^{-5}	0.043	14
		20		6.7	1800	0.16 (2.8)	0.33	0.001	1.6	2.5	0.1	1500	0.76	40*	2750	10^{-4}	0.011	55
	10	5	1	1.7	460	0.33 (2)	0.66	0.004	1.6	1.2 (2.1)	0.67	20	1.5	18	2650	2×10^{-5}	0.043	14
		20		6.7	1800	0.16 (2.8)	0.33	0.001	1.6	1.8 (2.6)	0.29	1060	5.3	40*	2750	10^{-4}	0.011	55
Bohm Plasma	3	5	0.42	2.4	650	0.2 (2.2)	0.55	0.003	1.1	2.5	0.34	330	0.46	18	2650	3×10^{-5}	0.031	14
		20	0.21	4.7	1270	0.29 (2.6)	0.40	0.0015	2.3	2.5	0.12	1040	0.64	40**	2750	7×10^{-5}	0.016	55
	10	5	0.77	1.3	350	0.49 (1.9)	0.76	0.009	2.1	0.5 (1.5)	0.66	20	0.77	18	2650	1.5×10^{-5}	0.057	14
		20	0.38	2.6	700	0.70 (2.2)	0.53	0.0025	4.2	2.5	0.55	150	5.3	74	2850	1.5×10^{-4}	0.029	55

* $\bar{T}_s=175$ eV

** $\bar{T}_s=125$ eV

From the equations (14), (15) and (16), the heaviest impurity, Ne, is the best impurity of the three. Much heavier impurities than Ne have a much larger cooling effect, but the radiation loss is still large with $T_e > 1$ keV. For example, P_T (Fe) $\approx$ 12 P_T (Ne) and $\int_{1\,\mathrm{keV}}^{3\,\mathrm{keV}} P_R(\mathrm{Fe})dT$ has the same value of P_T (Fe) which is an integrated value from 5 eV to 1 keV. Then the heavy impurities cool also the plasma near the center. For this reason, we employ Ne impurity and assume a constant fraction (γ_{Ne}%) in a plasma column.

The radiation loss near the edge plasma is roughly given by the following equation.(13)

$$P_{RE} = \sqrt{2K_{eff} \int_{T_1}^{T_2} P_R dT} \quad S \tag{17}$$

K_{eff} is the effective heat conduction in the edge plasma and is assumed the value shown in the Table 3. The integrated value for Ne impurity is given as follows.(12)

$$\int_{T_1}^{T_2} P_R dT = 6.5 \times 10^{-51} \gamma_{Ne} \bar{n}_{eE}^2 \ (J^2/sm^3) \tag{18}$$

For a plasma with an empirical scaling, the following equation is obtained.

$$P_{RE}/S = 7.2 \times 10^{-16} \quad \gamma_{Ne} \ \bar{n}_{eE} \tag{19}$$

For a plasma with a Bohm type scaling, the following equation is obtained.

$$P_{RE}/S = 1.6 \times 10^{-25} \bar{n}_{eE} \sqrt{\gamma_{Ne} \bar{n}_e \bar{T}/B_T} \tag{20}$$

To avoid the serious effect to the plasma confinement, γ_{Ne} is assumed less than 2.5% which causes $Z_{eff} \leq 3.3$. The reduction of α is listed in Table 3. It is clear that the method is effective to reduce α in a high density tokamaks. The scrape-off layer plasma, however, is not sufficient cold with a large energy input as shown in the same Table 3.

This effect may occur in the present tokamaks especially in tokamaks with a rather large fraction of low-z impurities and a high density.

3.2 Parameter γ

γ is the ratio of the heat flux to the particle flux times electron temperature and γ=5–8 with a normal sheath.5) 6) The electron emission from the neutralizer plate or the limiter increases γ and the maximum value of γ is obtained with no sheith potential and is about 80 for a hydrogen plasma which is obtained under the assumption of 'free stream'. The free stream of electrons is obtained with one cold electron emission for each electron inflow and about 40 times electrons of the particle flux have to emit to maintain the charge neutrality of the scrape-off layer. In Table 3, the parameters of the scrape-off layer and the necessary emission current are listed with $\gamma \leq 80$. Without the sheath potential, the critical temperature which induces the serious impurity build-up is higher, typically 100 eV, because of no acceleration of ions near the neutralizer plate or the limiter. For this reason, the listed electron temperature is sufficient low.

The first possibility is the electron emission from a hot neutralizer plate or a hot limiter,(14) and the necessary temperature of the surface is also listed in Table 3. The required temperature is rather high and the evaporation from the neutralizer plate or the limiter has to be considered. The evaporation rate is also listed in Table 3 and does not seem serious. The evaporation, however, becomes very serious if some heat flux from a plasma is concentrated on a small area of the neutralizer plate or the limiter. The other problem is whether the hot surface can be limitted only on the necessary area or not. When a larger area is necessary, the evaporation rate becomes large. For these reason, this method has a serious risk. In some present tokamaks, however, the hot spot is observed and the electron emission effect (increase of γ) may occur.

The secondary electron emission can also decrease γ but the increase of γ may be less than a factor of 2 which corresponds to one secondary electron emission for each ion inflow.

The other possibility of increasing γ is a cold plasma layer near the neutralizer plate. In this scheme, the problem is whether the equilibrium between the cold plasma and the scrape-off layer plasma can be maintained or not.

3.3 Parameter s

(1-s) is the effective recycling rate in a scrape-off layer and s is increased with plasma sources in a scrape-off layer. The required value of s to obtain a plasma with T_{eS}=20eV and the necessary plasma flux as a plasma source are listed in Table 3. An active plasma source and a passive plasma source are considered.

An example of the active plasma source is a gas source with some ionization methods such as discharge and rf heating. In this case, problems are how we can obtain a pure plasma with a large flux and how we can pump out the large neutral particle flux after neutralization.

The passive plasma source is the ionization by the scrape-off layer plasma. The scrape-off layer should be thick which ionizes the refrected particles from the neutralizer plate, or the cold gas concentrated near the neutralizer plate should be ionized. In the later case, the equilibrium between the scrape-off layer and the cold gas (or a cold plasma) has to be considered. The former case is discussed below.

To ionize a hydrogen atom with velocity V_0, the line density $n_{eS}d_S$ of the scrape-off layer has to satisfy the following equation.

$$n_{eS}d_S > V_0/\langle\sigma v\rangle_{Hi} \qquad (21)$$

where $\langle\sigma v\rangle_{Hi}$ is the ionization rate and is $1.4\times10^{-14}m^{-3}s^{-1}$. V_0 is around 1.8×10^4 m/s because the cx process is dominant and the hydrogen atom has the energy of the scrape-off layer with T_S=20 eV. The following condition is obtained.

$$n_{eS}d_S > 1.3\times10^{18}\ m^{-2} \qquad (22)$$

This value seems rather high. The line density, however, becomes higher ($d_S \propto 1/s^{1/2}$ and enhancement of the ionization) once the scrape-off layer has the shielding property for hydrogen atoms. For this reason, this scheme seems realistic if we have a temporal or steady plasma source in a scrape-off layer. The fuel may be supplied from the scrape-off layer. The density profile and particle balance with s << 1, however, can not be discussed by using eq.7). This problem is discussed in 4.

3.4 The Last Term of Equation 7)

The last term of the equation 7) is the radiation cooling effect by impurities in the scrape-off layer and the discussion is similar to that of 3.1. The impurities, can be concentrated near the neutralizer plate ($\delta_i < 1$) by the space potential as discussed by D. Meade. Even in this case, however, the serious impurity build-up has to be eliminated because of the impurity flow by the diffusion process, and the temperature in the scrape-off layer is also kept low.

An example where T_{eS}=20 eV and δ_i=0.25 with Fe impurity is discussed. In this case, the following parameters are given as follow.

$s = 1-\gamma_i Z$, $Z = 6$, $\Sigma P_Z = 283.5$ eV and

$R(T_e) = 1.5\times10^{-13}$ eV/sm^3.

The equation 7) is written as follows.

$$\frac{\bar{T}}{\bar{T}_s}\left(\frac{3\alpha}{\gamma}\,\frac{\tau_p}{\tau_E}\right)s = 1 + \gamma_i\left(1.8+9\times10^{\;4}(Rm)^{3/2}s^{1/2}B_T{}^{1/2}\,\frac{na}{\tau_p}\,\left(\frac{\bar{n}_{es}}{n_{es}}\right)^2\ell\right) \qquad (23)$$

where $n=\bar{n}_e/10^{19}$.

The last term is 2.5 γ_i or less for A and 3 γ_i or less for B, and this effect is rather small. The radiation cooling effect at $T_{eS} = 20$ eV is large for Oxygen which gives three times of that of Fe. The radiation cooling effect is largely enchanged by increasing the density in the scrape-off layer which is discussed in 4. We can also enhance this effect by increasing δ_i and this effect with $\delta_i = 1$ is same as that discussed in 3.1.

4. Shielding Property

If the temperature in the scrape-off layer is kept low, the shielding property for impurity influx is easily obtained as shown below.

The condition of the shielding property for Oxygen of 5eV by a plasma with $\bar{T}_S$=20 eV is

$$n_{es}d_s \gg \frac{V_{i\perp}}{\langle\sigma v\rangle_{ii}} = 2.8\times10^{16}\ \mathrm{m}^{-2} \tag{24}$$

If $n_{eS}d_S = 6.5\times10^{16}\ \mathrm{m}^{-2}$, the influx rate is only 10% and the shielding effect is sufficiently large. The following condition has to be satisfied to obtain this line density or a higher value.

$$\frac{n_e a}{s\tau_p} \geq \frac{1.3\times10^{17}}{\tau_\parallel} = 7.4\times10^{20}/\mathrm{Rm} \tag{25}$$

For a plasma with the empirical type scaling, this condition is written as follows.

$$\frac{\mathrm{Rm}}{\mathrm{sa}} \geq 7.4 \tag{26}$$

This condition is always satisfied. For a plasma with the Bohm type scaling, the condition is written by the following equation and is satisfied with a high density.

$$\frac{\mathrm{Rm}\ \bar{n}_e\bar{T}(\mathrm{keV})}{a\ B_T\ s} \geq 1.5\times10^{20} \tag{27}$$

The shielding for metallic impurities is easy. Then, the problem is whether the ionized impurities flow into the main plasma column during the transit time or not.

In practice, the most appropriate impurity transport model would be a combination of neoclassical transport and anomalous diffusion with the magnitude of the field particle diffusion. The diffused width $d_{i\Delta}$ and the inward diffusion distance d_{iI} are roughly given by the following equations for 20 eV plasma.

$$d_{i\Delta} = \sqrt{\tau_{11}D_\perp} \tag{28}$$

$$d_{iI} = 3\times10^{-20}\,\frac{Zn_{es}}{B_T^2}\,\frac{\tau_\parallel}{d_s}\ \text{15)} \tag{29}$$

$d_{i\Delta}$ and d_{iI} have to be much less than $d_s \times \ell n(\frac{n_{es}}{n_{e1}})$ where $n_{e1} d_s = 0.7 V_{i\perp}/\langle\sigma v\rangle_{ii}$. The first condition is

$$\frac{1}{s}\ \ell n\, \frac{n_{es}}{n_{e1}} >> 1 \tag{30}$$

Assuming Fe impurities with 5 eV, the condition is written as follows.

$$\frac{1}{s}\ \ell n \frac{n_{es}}{n_{e1}} = \frac{1}{s}\ \ell n\, \frac{n_{es} d_s}{6\times10^{15}} >> 1 \tag{31}$$

This condition is similar to eq.(26) and is usually satisfied. If we assume O impurity, the condition is not satisfied.

For the inward diffusion, the following condition is obtained under assumptions of $z = 6$, $D_\perp = 0.13/B_T$ and $\tau_\parallel = 1.8\times10^{-4}\times Rm$.

$$\frac{\bar{n}_e a s}{\tau_p} \sqrt{\frac{Rm}{B_T}}\ (\ell n\, \frac{n_{es}}{n_{e1}})^{-1} << 7.7\times10^{19} \tag{32}$$

The magnitude of the left side is not very smaller than the right hand side except $s \lesssim 0.1$.

From the above estimation, the impurity influx from the wall is easily ionized in a low temperature scrape-off layer but a rather large fraction of them flow into the main plasma column except $s \lesssim 0.1$. If this problem is serious, some controls of the density profile in the scrape-off layer are necessary: a peaked profile as discussed by D. Meade.$^{16)}$ The flat profile is discussed below.

With an active plasma source or a thick scrape-off layer, the line density in the scrape-off layer profile is determined by the density of the flat profile and the transport coefficients of the scrape-off layer inspite of the particle flux from the main plasma column as discussed in 2. An ideal case whose the density profile is schematically shown in Fig. 1 is discussed.

We assume the density n_e is constant at $o \leq r \leq a+d_1$ and decreases exponentially from $r \geq a+d_1+d_2$ which means a complete recycling at $a \leq r \leq a+d_1$ and no recycling at $r \geq a+d_1+d_2$. The following equation is also assumed.

$$n_{es} d_s = 0.5\ V_o/\langle\sigma v\rangle_{Hi} \tag{33}$$

where notations are same as in 3. For the energy conservation, the following equation is obtained.

$$\frac{3\alpha a\tau_{11}\bar{T}}{2\gamma d\tau_E\bar{T}_s} = 1 + \frac{\gamma_i}{\gamma\bar{T}_s}\left(\Sigma P_z + \frac{\bar{n}^2_{ed}}{n_e}\delta_i\tau_{11}R(T_e)\ell\right) \tag{34}$$

where

$$d = d_1 + \frac{n_e+n_{es}}{2n_e}d_2 + \frac{n_{es}}{n_e}d_s \tag{35}$$

$$\bar{n}^2_{ed}d = n_e^2 d + \overline{\left(\frac{n_e+n_{es}}{2}\right)^2}d_2 + \overline{n^2_{es}}\,d_s \tag{36}$$

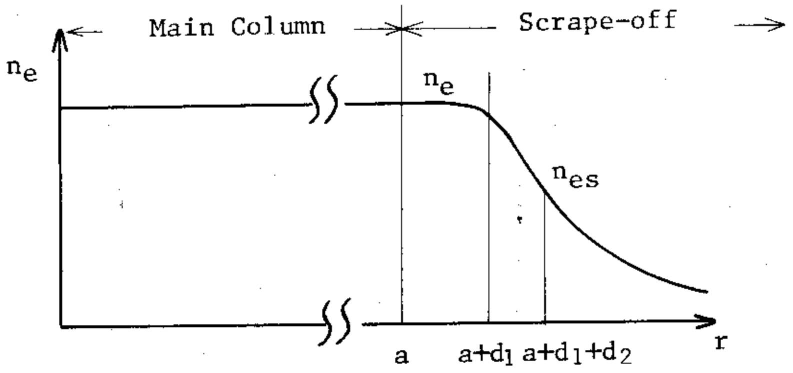


Fig. 1 Flat density profile

If we assume α=0.7, γ=7.8 and γ_i=0, an expected profile which gives $\bar{T}_s$= 20 eV is shown in Fig. 2 for the reference tokamaks with a density of 10^{20} m^{-3} and the higher input. If we fix $\bar{T}_s$, d_s is increased by haivng some additional energy input in a scrape-off layer and is decreased by increasing the parameters, $1/\alpha$, γ and the last term of eq.(34). In the same figure, d_s is shown in the case of γ_{Ne}= 1% which increases $1/\alpha$. With this flat density profile, the last term of eq. (34) is effective and is about 30 times larger than the value discussed in 3.4.

In a thick scrape-off layer, however, the temperature profile may be also important and the above simple estimation may be variable.

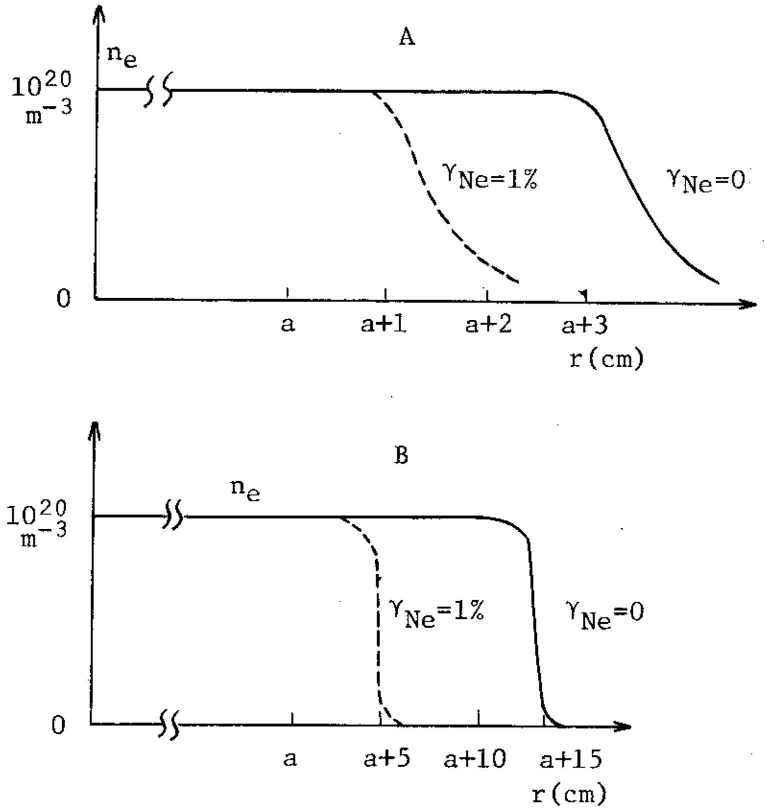


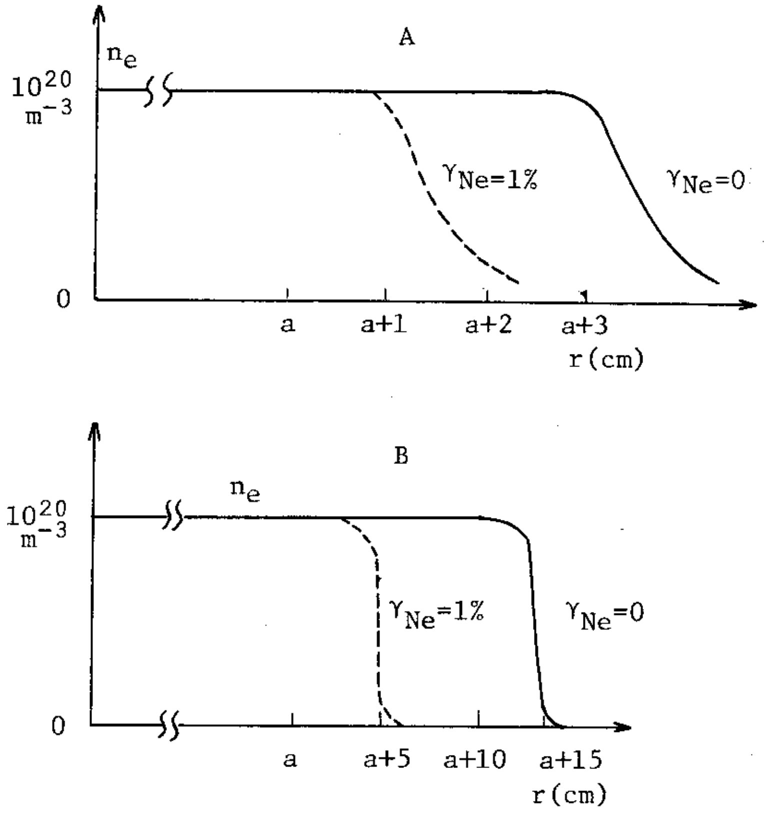
Fig. 2 Expected Profile in Scrape-off Layer Plasma
A (input 5 MW)
B (input 20 MW)
$\alpha_0=0.7$, $\gamma=7.8$, $\bar{T}_s=20\text{eV}$, Emperical Plasma

5. Conclusions

The scrape-off layer is discussed by using a simple model and the following conclusions are obtained.

In the present medium or large tokamaks, the edge temperature is estimated less than 60 eV which seems to be adjusted by the radiation loss. In a future large tokamak some controls of a scrape-off layer is necessary to eliminate serious impurity contamination, and one of suitable scrape-off layers is a cold and thick plasma which does not induce the serious impurity production on a neutralizer plate (or a limiter) and shields the impurity influx from the first wall. Some possible methods obtaining this cold and thick scrape-off layer are discussed, and edge cooling by a light impurity and a cold plasma source in a scrape-off layer seems useful.

In the above simple discussions, important effects such as cx, profile and temperature difference between electrons and ions are not included and numerical calculation is necessary to discuss in more detail.



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