JAERI-Research
95-052

EVALUATION OF DIVERTOR AND SCRAPE-OFF PLASMA PARAMETERS USING SIMPLE TWO POINT MODEL

July 1995

Keisuke NAGASHIMA

日本原子力研究所
Japan Atomic Energy Research Institute

編集兼発行　日本原子力研究所
印　　　刷　いばらき印刷㈱

Evaluation of Divertor and Scrape-off Plasma Parameters Using Simple Two Point Model

Keisuke NAGASHIMA

Department of Fusion Plasma Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received June 19, 1995)

A simple two point model was developed in order to evaluate divertor and scrape-off plasma parameters. The advantage of this model is a capability for evaluating not only the plasma parameters but also the neutral parameters, like the recycling rate and the particle multiplication factor, without detailed numerical simulations. This model was applied to JT-60 Super Upgrade for determining the guideline values of the divertor design. It was found that the particle pumping rate (the pumped flux over the total flux to the divertor plates) should be about 0.5% and the rate of back-flow neutral flux should be under 2%, in order to obtain enough He-ash exhaust and cold-dense divertor plasma in the steady state operation.

Keywords: JT-60 Super Upgrade, Divertor, Scrape-off Layer, Recycling Rate, Particle Multiplication Factor

JAERI-Research 95-052

簡易２点モデルを用いたダイバータ及びスクレイプオフのプラズマパラメータ評価

日本原子力研究所那珂研究所炉心プラズマ研究部
永島　圭介

（1995年６月19日受理）

ダイバータ及びスクレイプオフ領域のプラズマパラメータを評価するために簡易な２点モデルを開発した。このモデルの特長は、プラズマパラメータだけでなく、リサイクリング率や粒子増倍率といった中性粒子パラメータについても、詳細な数値計算なしに評価できることである。このモデルを定常炉心試験装置（ＪＴ－６０ＳＵ)のダイバータ設計に適用して、ガイドラインとなる設計値を決定した。定常放電において十分なヘリウム灰排気を実現し、かつ、低温高密度ダイバータプラズマを得るためには、ダイバータへの全粒子束の0.5%を排気し、主プラズマ側へ逆流する中性粒子束を２％以下にする必要があることを明らかにした。

那珂研究所：〒311-01　茨城県那珂郡那珂町向山801-1

Contents

目次

1. Introduction

For development of the next-step tokamak fusion reactor (like ITER [1] and SSTR [2]), optimization of the divertor is one of the most important issues. Main functions of the divertor are heat removal and particle exhaust. However, on the both aspects, the optimized divertor concept has not been demonstrated.

About the heat removal, divertor plate materials must be tolerable with the high heat flux density over 10 MW/m^2. In order to reduce the heat flux density, several methods have been proposed and investigated. They are declination of the divertor plates, strike-point swing, radiative cooling [3], gas target divertor [4] and so on. Geometrical effects of the magnetic flux are used in the former two methods, but the reduction of the heat flux density is not enough only for these two methods. Hence, it is necessary to modify the divertor plasma to reduce the damage of the plasma-facing materials.

About the particle exhaust, neutral particle pressure increases in the divertor region and the particles are pumped effectively. In particular, in order to avoid the plasma dilution, He-ash and impurity species must be pumped with an adequate pumping speed. Therefore, it is necessary that the particle recycling to the main plasma is suppressed and the impurity shielding effect [5] is enhanced. In addition, in order to reduce the heat flux density and the sputtering damage, high density and low temperature plasma should be generated in the divertor region.

Up to now, many efforts have been devoted to the investigation and the optimization of the divertor on the above mentioned standing points. However, we need more examination of the divertor plasma behavior. Numerical simulation [6, 7] is an effective tool for studying the divertor plasma parameters and is helpful for the divertor design. However, the numerical simulation is time-consuming and it is not adequate for the design parameter survey. Hence, we think that the more simple model to evaluate the plasma parameters is useful. Here, a simple two point model is described and an application to JT-60 Super Upgrade is shown.

2. Two Point Model

Here, we think the plasma parameters at two points, the divertor plate and the scrape-off layer, which are connected with the connection length $L_{//}$ parallel to the magnetic field line. The connection length is estimated as $L_{//} = \pi qR$, where q is the safety factor and R is the major radius. The radial width Δ in the scrape-off layer is expanded by a factor of h on the divertor plate.

The particle balance is illustrated in Fig.1, where the representations are

Γ_1 : gas puffing flux to main region
Γ_2 : gas puffing flux to divertor region
Γ_α : birth flux in the core plasma
Γ_d : flux to the divertor plate
$\Gamma_{through}$: neutral flux through the divertor throat
Γ_{main} : flux across the separatrix surface
$\Gamma_{re\text{-}ion}$: re-ionized flux in the divertor region
Γ_{pump} : pumped flux

β_1 : penetration rate from the main region to the core plasma
β_2 : penetration rate from the divertor region to the core plasma
η : rate through the divertor throat

($\Gamma_{re\text{-}ion}$ and η are not shown in the figure.) The above parameters have the following relations of

$$\Gamma_{through} = \eta(\Gamma_d+\Gamma_2) \tag{1}$$

$$\Gamma_{main} = \Gamma_\alpha+\beta_2(\Gamma_d+\Gamma_2)+\beta_1(\Gamma_1+\Gamma_{through}) \tag{2}$$

$$\Gamma_{re\text{-}ion} = (1-\beta_2)(\Gamma_d+\Gamma_2)-\Gamma_{through}-\Gamma_{pump} \tag{3}$$

$$\Gamma_d = \Gamma_{main}+\Gamma_{re\text{-}ion}+(1-\beta_1)(\Gamma_1+\Gamma_{through}) \tag{4}$$

$$\Gamma_1+\Gamma_2+\Gamma_\alpha = \Gamma_{pump} \tag{5}$$

$$A_{pump} = \Gamma_{pump}/(\Gamma_d+\Gamma_2) \tag{6}$$

$$Y = \Gamma_d/\Gamma_{main} \tag{7}$$

where A_{pump} is the pumping rate and Y is the particle multiplication factor.

Figure 2 shows the particle recycling. In the figure, N, τ and R are the main particle number, the particle confinement time and the recycling rate. N_α is the particle number generated from the flux Γ_α and they are related with the confinement time τ_α. N_β is the particle number generated from the neutral flux and they are related with the confinement time τ_β. Using these relations, particle balance equations are written as

$$\frac{dN}{dt} = -\frac{N}{\tau} + R\frac{N}{\tau} + \Gamma_\alpha + \beta_1\Gamma_1 + (\beta_2+\eta\beta_1)\Gamma_2 \tag{8}$$

$$N = N_\alpha + N_\beta \tag{9}$$

$$\frac{N}{\tau} = \frac{N_\alpha}{\tau_\alpha} + \frac{N_\beta}{\tau_\beta} \tag{10}$$

$$\frac{dN_\alpha}{dt} = -\frac{N_\alpha}{\tau_\alpha} + \Gamma_\alpha \tag{11}$$

$$\frac{dN_\beta}{dt} = -\frac{N_\beta}{\tau_\beta} + R\left(\frac{N_\alpha}{\tau_\alpha} + \frac{N_\beta}{\tau_\beta}\right) + \beta_1\Gamma_1 + (\beta_2+\eta\beta_1)\Gamma_2 \tag{12}$$

In a steady state condition, the particle numbers are given as

$$N_\alpha = \tau_\alpha\Gamma_\alpha \tag{13}$$

$$N_\beta = \tau_\beta^*\{R\Gamma_\alpha+\beta_1\Gamma_1+(\beta_2+\eta\beta_1)\Gamma_2\} \tag{14}$$

$$\tau_\beta^* = \tau_\beta/(1-R) \tag{15}$$

From Eqs (13) to (15), the flux across the separatrix surface is given as

$$\frac{N}{\tau} = \Gamma_{main} = \frac{\Gamma_\alpha+\beta_1\Gamma_1+(\beta_2+\eta\beta_1)\Gamma_2}{1-R} \tag{16}$$

The flux to the divertor is given from Eqs (7) and (16)

$$\Gamma_d = \frac{Y}{1-R}\{\Gamma_\alpha+\beta_1\Gamma_1+(\beta_2+\eta\beta_1)\Gamma_2\} \tag{17}$$

, from Eqs (2) and (16)

$$\Gamma_d = \frac{1}{(\beta_2+\eta\beta_1)} \frac{R}{1-R} \left\{\Gamma_\alpha+\beta_1\Gamma_1+(\beta_2+\eta\beta_1)\Gamma_2\right\} \tag{18}$$

and from Eqs (5) and (6),

$$\Gamma_d = \frac{1}{A_{pump}}\Gamma_\alpha + \frac{1}{A_{pump}}\Gamma_1 + \frac{1-A_{pump}}{A_{pump}}\Gamma_2 \tag{19}$$

Using Eqs (17) to (19), the recycling rate is

$$R = (\beta_2+\eta\beta_1)Y \tag{20}$$

and the multiplication factor is

$$Y = \frac{\Gamma_\alpha+\Gamma_1+(1-A_{pump})\Gamma_2}{(A_{pump}+\beta_2+\eta\beta_1)\Gamma_\alpha+(\beta_1 A_{pump}+\beta_2+\eta\beta_1)\Gamma_1+(\beta_2+\eta\beta_1)\Gamma_2} \tag{21}$$

The multiplication factor is given as

$$Y = \frac{1}{A_{pump}+\beta_2+\eta\beta_1} \quad \text{(for birth flux only)} \tag{21-a}$$

$$Y = \frac{1}{\beta_1 A_{pump}+\beta_2+\eta\beta_1} \quad \text{(for main gas puffing only)} \tag{21-b}$$

$$Y = \frac{1-A_{pump}}{\beta_2+\eta\beta_1} \quad \text{(for divertor gas puffing only)} \tag{21-c}$$

Here, it is assumed that the divertor parameters are symmetry between the inner-side and the outer-side. The particle and the heat flux on the plates are given as

$$\Gamma_d = 2\cdot 2\pi R\cdot h\Delta_\Gamma\cdot \frac{B_p}{B_t} M_d c_s n_d \tag{22}$$

$$q_d = 2\cdot 2\pi R\cdot h\Delta_q\cdot \frac{B_p}{B_t} \gamma T_d M_d c_d n_d \tag{23}$$

where Δ_Γ and Δ_q are the e-holding lengths of the particle and the heat flux. B_p and B_t are the poloidal and the toroidal magnetic field. n_d and T_d are the density and the temperature on the divertor plate. c_s is the sound velocity and M_d is Mach number of the parallel flow on the plate. γ is the total heat transmission coefficient and its value is about 7 [8, 9]. The ratio of B_p/B_t is given approximately as

$$\frac{B_p}{B_t} = \frac{\pi a}{L_{//}} \tag{24}$$

The e-holding lengths of the particle and the heat flux are given as

$$\frac{1}{\Delta_\Gamma} = \frac{1}{\Delta_n} + \frac{1}{2\Delta_T} \tag{25}$$

$$\frac{1}{\Delta_q} = \frac{1}{\Delta_n} + \frac{3}{2\Delta_T} \tag{26}$$

where Δ_n and Δ_T are the e-holding lengths of the density and the temperature profiles.

As the radiation and the ionization energy loss increase near the divertor plate, the heat flux decreases toward the divertor plate. The heat flux on the plate is the flux across the separatrix surface $q_\perp$ minus the radiation and the ionization energy loss, which is written as

$$q_d = (1-f_{rad})q_\perp - \xi(1-\frac{1}{Y})\Gamma_d \tag{27}$$

where f_{rad} is the radiation loss fraction and ξ is the ionization energy loss per particle. From Eqs (22), (23) and (27), the divertor temperature is given as

$$\gamma T_d = \left\{\frac{(1-f_{rad})q_\perp}{\Gamma_d} - \xi(1-\frac{1}{Y})\right\}\frac{\Delta_\Gamma}{\Delta_q} \tag{28}$$

On the other hand, using the classical electron parallel conductivity, electron temperature in the scrape-off layer is obtained as [10]

$$T_s^{7/2} = \frac{49}{4}\frac{L_{//}^2 q_\perp}{2\kappa_0 \Delta_T A_{surface}} + T_d^{7/2} \tag{29}$$

where $\kappa_0 = 7.286\times10^{21}$ [for m, eV unit].

In the scrape-off layer, the particle conservation equation is given as

$$\Delta_\Gamma \cdot \Gamma_{//} = L_{//} \cdot \Gamma_\perp \tag{30}$$

where the parallel and the perpendicular particle flux are given as

$$\Gamma_{//} = Mc_s n_s \tag{31}$$

$$\Gamma_{\perp} = D\frac{n_s}{\Delta_n} \tag{32}$$

From Eqs (30) to (32), the density scale length is given as

$$\Delta_n = \sqrt{\frac{L_{//}D}{Mc_s}\left(1+\frac{\Delta_n}{2\Delta_T}\right)} \tag{33}$$

Experimentally, it was found that the ratio of Δ_T/Δ_n is 1.5 to 2 [11, 12]. Considering the parallel electron heat flux with the classical conductivity, $\Delta_q = 2/7\Delta_T$. From this and Eq.(26), the ratio of Δ_T/Δ_n is evaluated to be 2. Hence, $\Delta_T/\Delta_n = 2$ is assumed in the following sections.

The divertor temperature and the scrape-off temperature are evaluated from Eqs (28) and (29), respectively. The divertor density is evaluated from Eq.(22). Hence, the scrape-off density is obtained using the parallel momentum conservation of

$$n_d T_d = \frac{1-f_{cx}}{1+M_d^2} n_s T_s \tag{34}$$

where fcx is the parallel momentum loss fraction due to charge exchange reaction.

Next, we consider the neutral particle behavior. The neutral particle released from the wall or the divertor plate is ionized in the plasma region. In general, ionization rate coefficient is smaller than that of charge exchange reaction. Hence, it is considered that the neutral particle behaves as random walk process until it is ionized. The illustrative model is shown in Fig.3. Hence, it is thought that the neutral particle behavior is treated as a diffusion process [13] of

$$\frac{\partial n_0}{\partial t} = D\frac{\partial^2 n_0}{\partial x^2} - n_0 n_e <\sigma v>_{ion} \tag{35}$$

where $<\sigma v>_{ion}$ is the ionization rate coefficient. The steady state solution is

$$n_0(x) = n_0(0)\exp(-\frac{x}{\lambda_{ion}}) \tag{36}$$

and the ionization length λ_{ion} is given as

$$\frac{D}{\lambda_{ion}^{2}} = n_e<\sigma v>_{ion} \tag{37}$$

Using the mean free pass length for the charge exchange reaction of

$$\lambda_{cx} = \frac{\zeta\, v_0}{n_i<\sigma v>_{cx}} \tag{38}$$

the diffusion coefficient D is evaluated as

$$D = \zeta^2 \frac{v_0^2}{n_i<\sigma v>_{cx}} \tag{39}$$

where ζ is geometrical factor and $\zeta = 2.0/\pi$. Hence, the ionization length is obtained as

$$\lambda_{ion} = \frac{\zeta\, v_0}{\sqrt{n_e n_i<\sigma v>_{ion}<\sigma v>_{cx}}} \tag{40}$$

In the real condition, the birth neutral from the wall has a low energy and it gets the thermal energy after a charge exchange reaction. In addition, some neutrals escape from the plasma region after the charge exchange. Including these effects, the penetration ratio is given as

$$\beta = C_1 \cdot C_2 \cdot \exp(-\frac{L_{sol}}{\lambda_{ion}}) \tag{41}$$

where L_{sol} is the effective width between the vacuum region and the main plasma region. C_1 and C_2 are the constants reflecting the above mentioned effects.

In a case with the thick scrape-off region of $L_{sol} \geq \lambda_{cx}(E_0=5eV)$, the neutral energy is $\frac{1}{2}mv_0^2 = T_i$ and the constants are

$$C_1 \approx \frac{<\sigma v>_{cx}}{<\sigma v>_{ion} + <\sigma v>_{cx}}, \quad C_2 \approx 1-\varepsilon + \varepsilon \exp(-\frac{L_{sol}}{\lambda_{cx}}), \quad \varepsilon = 0.5 .$$

In an another case of $L_{sol} < \lambda_{cx}(E_0=5eV)$, the neutral energy is $\frac{1}{2}mv_0^2 = 5$ eV and the constants are $C_1 \approx 1$, $C_2 \approx 1-\varepsilon' + \varepsilon' \exp(-\frac{L_{sol}}{\lambda_{cx}})$, $\varepsilon' = 0.2$.

The values of ε and ε' were determined from comparing with the Monte-Carlo simulation.

3. Application to JT-60 Super Upgrade

JT-60 Super Upgrade (JT-60SU) [14] is a tokamak device, which is planned to succeed to the JT-60 equipment. The mission of JT-60SU is to establish integrated basis of physics and technology for steady state tokamak reactor. The physics goal is a simultaneous achievement of stable, steady-state and fully current-driven plasma with high confinement, high bootstrap current fraction and cold radiative divertor.

Here, the divertor and scrape-off plasma parameters of JT-60SU are evaluated using the above mentioned simple two point model. Firstly, an example of input parameters and the calculated results is shown as

```
========        Input Parameters          ========

 >diffusion< 0=input-value,1=Bohm:      1
 diffusion coefficient      [m2/s]:     .500000
 total heating power          [MW]:     60.0000
 radiation loss fraction          :     .500000
 CX momentum loss fraction        :     .000000
 average mass                     :     2.00000
 pumping rate                     :     5.000000E-03
 penetration rate (main)          :     .000000
 penetration rate (divertor)      :     .000000
 through rate from div.to main    :     2.000000E-02
 input gas (main)       [Pa.m3/s]:      15.0000
 input gas (divertor)   [Pa.m3/s]:      .000000
 pellet/alpha particle       [/s]:      .000000
 toroidal field               [T]:      6.25000
 plasma current              [MA]:      5.00000
 major radius                 [m]:      4.80000
 minor radius                 [m]:      1.40000
 ellipticity                      :     1.80000
 triangularity                    :     .400000
 flux expansion factor            :     4.00000

  ==========           RESULTS            ==========

  aspect ratio                       :   3.42857
 safety factor-95                    :   7.51435
 plasma surface area            [m2]:   386.275
 plasma volume                  [m3]:   334.272
 connection length               [m]:   113.314
 diffusion coef.              [m2/s]:   1.00632
```

```
scrape-off temperature           [eV]:  201.263
divertor temperature             [eV]:  19.3180
scrape-off density              [/m3]:  1.949890E+19
divertor density                [/m3]:  1.015739E+20
temperature scale length         [m]:  9.062853E-02
density scale length             [m]:  4.531427E-02
multiplication factor               :  172.197
recycling rate                      :  .800834
divertor particle flux          [/s]:  1.483200E+24
divertor heat flux             [eV/s]:  1.875000E+26
penetration rate (main)             :  .231324
penetration rate (divertor)         :  4.650679E-03
```

In the input parameters, the diffusion coefficient is given as a fraction for Bohm diffusion of $(1/16)T_s/B_t$. The above plasma parameters are standard values as a steady-state operation with high bootstrap current fraction over 60 %. For the design of the divertor function, the pumping rate and the through rate from divertor region to main region are critical parameters. The former is determined from geometrical shape of the divertor region, conductance of the exhaust port and pumping speed. The latter is mainly determined from the geometrical shape of the divertor region. In the closed divertor, where the through rate is small, the particle multiplication factor becomes large and the recycling rate becomes small, which is important in order to reduce He-ash concentration in the core plasma.

Figure 4 shows the temperature and the density on the divertor as a function of the pumping rate A_{pump}. The other parameters are same as those shown in the above. The penetration rate in the main region was calculated using $L_{sol} = \Delta_n$, and that in the divertor region was calculated using $L_{sol} = h\Delta_n$. In order to generate the dense and cold divertor plasma, A_{pump} is expected to be under 0.5 %. However, an appropriate pumping rate is necessary to exhaust He-ash satisfactorily. On this point, the recycling rate R must be under 0.8, which is evaluated from the condition of $\tau_{He}{}^*/\tau_E < 10$. Figure 5 shows the dependence of R on A_{pump}. In the figure, R decreases with A_{pump} under 0.7 %, but it increases with A_{pump} over 0.7 %. This reason is that the neutral penetration rate from the divertor region increases with A_{pump}.

Finally, an effect of the through rate η was examined. Figure 6 shows the dependence of R on η. From the figure, η should be designed under 2 % in order to satisfy the condition of $R < 0.8$. In the realistic divertor condition, the highest possible pass from the divertor to the core plasma is a space between the separatrix flux surface and the buffle plate in the private region. In this case, it is noted that the neutrals penetrate directly into the core region, without passing the scrape-off layer.

4. Conclusions

A simple two point model was developed in order to evaluate plasma parameters in the divertor and the scrape-off layer. Using this model, we can easily survey the design parameters and determine the critical parameter's values for the divertor design. The advantage of this model is a capability for evaluating not only the plasma parameters but also the neutral parameters, like the recycling rate and the multiplication factor, without detailed numerical simulations. In addition, the particle flux across the separatrix flux surface and the flux to the divertor plate can be evaluated from the input neutral flux, which is an externally controlled parameter. However, the model is too simple and the several input parameters, in particular, the penetration rate in the divertor region, should be evaluated from the more detailed numerical simulation.

This model was applied to JT-60SU for determining the design values of the divertor functions. In order to obtain the enough He-ash exhaust and the cold-dense divertor, the guideline values are found as $A_{pump} = 0.5\ \%$ and $\eta < 2\ \%$.

Acknowledgments

The author is grateful for many useful discussions with members of the JT-60 Team. In particular, I would like to thank Drs. K. Shimizu, T. Takizuka, M. Kikuchi and M. Nagami.

4. Conclusions

A simple two point model was developed in order to evaluate plasma parameters in the divertor and the scrape-off layer. Using this model, we can easily survey the design parameters and determine the critical parameter's values for the divertor design. The advantage of this model is a capability for evaluating not only the plasma parameters but also the neutral parameters, like the recycling rate and the multiplication factor, without detailed numerical simulations. In addition, the particle flux across the separatrix flux surface and the flux to the divertor plate can be evaluated from the input neutral flux, which is an externally controlled parameter. However, the model is too simple and the several input parameters, in particular, the penetration rate in the divertor region, should be evaluated from the more detailed numerical simulation.

This model was applied to JT-60SU for determining the design values of the divertor functions. In order to obtain the enough He-ash exhaust and the cold-dense divertor, the guideline values are found as $A_{pump} = 0.5$ % and $\eta < 2$ %.

Acknowledgments

The author is grateful for many useful discussions with members of the JT-60 Team. In particular, I would like to thank Drs. K. Shimizu, T. Takizuka, M. Kikuchi and M. Nagami.

References

[1] P. H. Rebut, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1994 (Proc. 15th Int. Conf. Seville, 1994), to be published.

[2] Y. Seki, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1990 (Proc. 13th Int. Conf. Washington, 1990), G-1-2

[3] M. Shimada, et al., J. Nucl. Mater. 176-177 (1990) 122

[4] M. L. Watkins, P. H. Rebut, 19th EPS Conf. on Controlled Fusion and Plasma Physics (Innsbruck 1992), Part II, 4-3

[5] J. Neuhauser, et al., Nucl. Fusion 24 (1984) 39

[6] D. P. Stotler, et al., J. Nucl. Mater. 196-198 (1992) 895

[7] D. A. Knoll, P. R. McHugh, J. Nucl. Mater. 196-198 (1992) 352

[8] P. C. Stangeby, G. M. McCracken, Nucl. Fusion 30 (1990) 1225

[9] B. Lee, J. D. Callen, Phys. Fluids B 5 (1993) 1647

[10] K. Borrass, Nucl. Fusion 31 (1991) 1035

[11] J. A. Tagle, et al., J. Nucl. Mater. 196-198 (1992) 409

[12] D. Buchenauer, et al., J. Nucl. Mater. 196-198 (1992) 133

[13] K. Nagashima, et al., J. Nucl. Mater. 220-222 (1995) 208

[14] H. Ninomiya, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1994 (Proc. 15th Int. Conf. Seville, 1994), to be published.

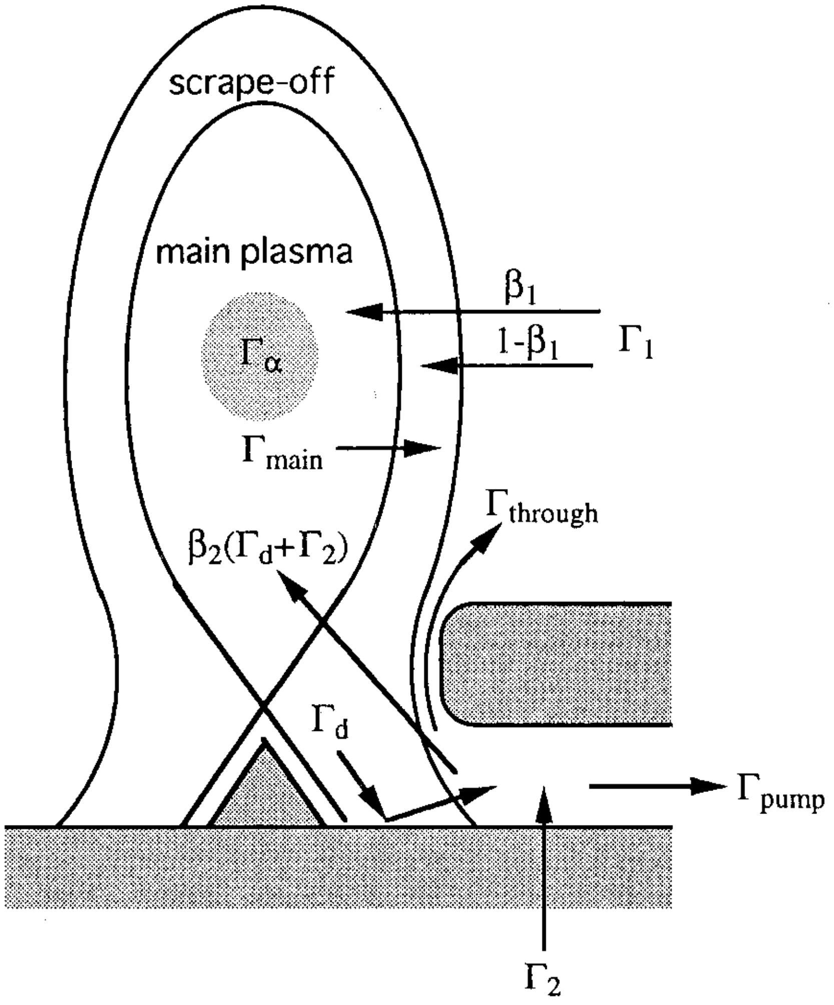

Fig. 1 An illustration of particle balance.

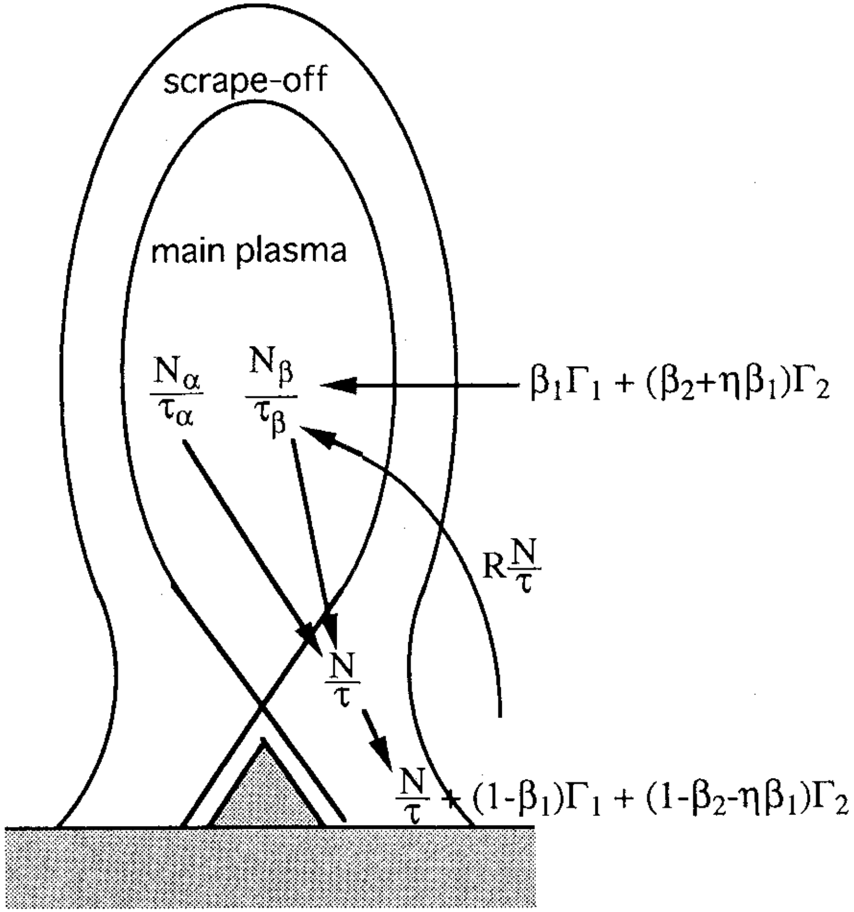

Fig. 2 An illustration of particle recycling.

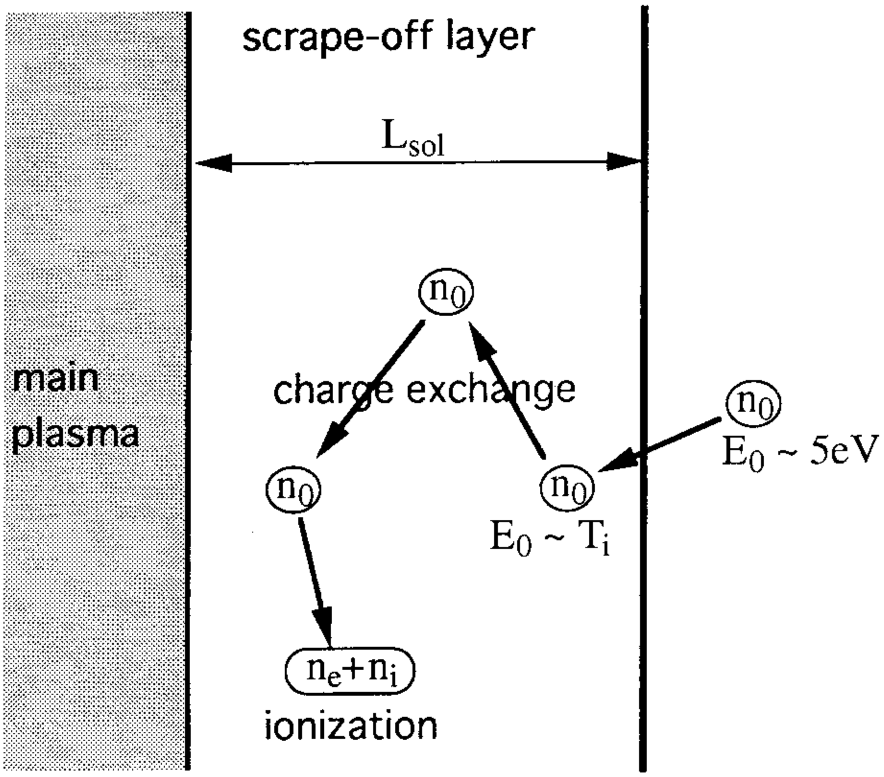

Fig. 3 Neutral particle model in the scrape-off layer.

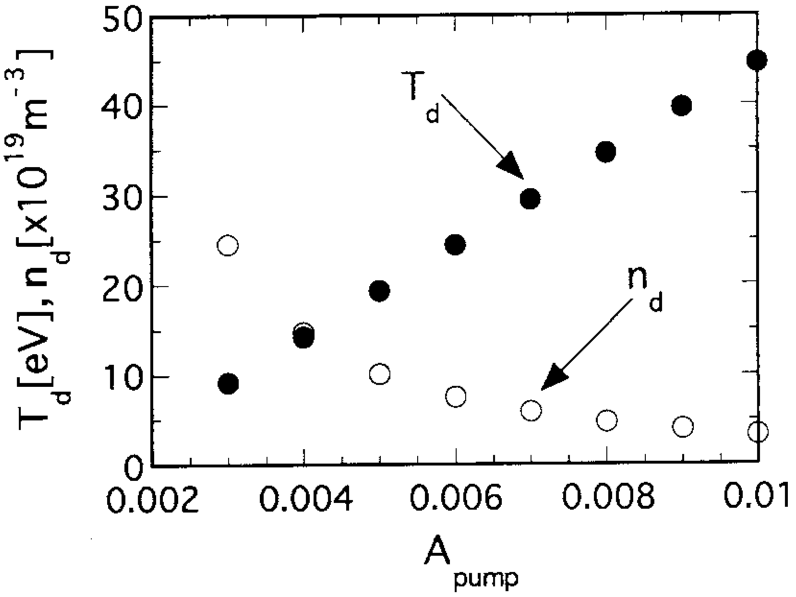

Fig. 4 Temperature and density on the divertor plate as a function of the pumping rate.

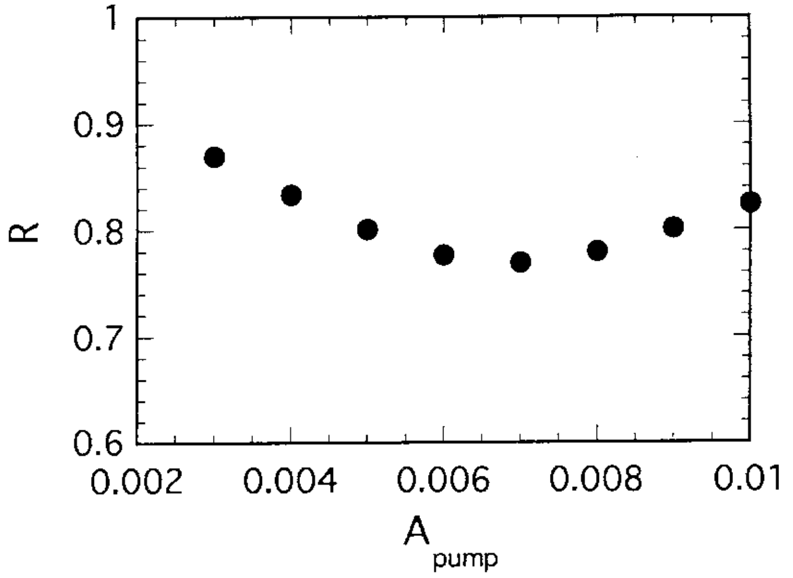

Fig. 5 Recycling rate as a function of the pumping rate.

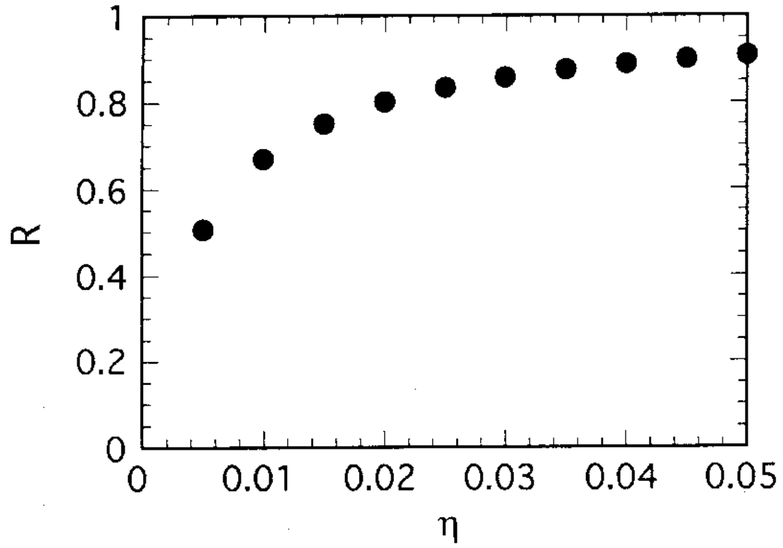

Fig. 6 Recycling rate as a function of the through rate.