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Journal of Nuclear Materials 241–243 (1997) 333–337

journal of nuclear materials

Kinetic analysis on impurity control and reduction of power transmission of a divertor plasma

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Abstract

A high-recycling divertor plasma is treated using a kinetic model to examine impurity retention and power exhaust by charge-exchange collisions in a divertor chamber in which magnetic field is expanded. Cold ions of fuel and ionized impurities are effectively trapped in the divertor chamber by the electrostatic potential caused by magnetic expansion if cold ion density is smaller than an upper limit. Charge-exchange collisions remove momentum of the plasma along field lines and reduce ion heat flow to the divertor plates through removal of energetic ions remarkably.

Keywords: Divertor plasma; Kinetic analysis; Electric potential and current; Energy deposition

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1. Introduction

The tokamak bundle divertor or the helical divertor of heliotron/torsatron type devices has magnetic field expanding towards divertor plates. The expanding magnetic field plays an important role in impurity control through formation of an electrostatic potential drop along magnetic field lines [1]: ionized impurities are retained in the divertor plasma by the electrostatic potential without flowing into the main plasma. Therefore, the expanding magnetic field is effective not only to reduce the power density on targets but also to hold impurities in the divertor chamber.

On the other hand, plasma–neutral interactions is expected to play an important role for realizing the radiative divertor concept. Remarkable reduction of the power transmission factor from larger than 8 to 2–5 with increasing particle recycling have been measured in large tokamaks, DIII-D [2] and JT-60 [3]. A possible explanation may be due to lowered energy of ions reaching the divertor tiles through plasma–neutral collisions as pointed out in [2,4]. In order to clarify the role of plasma–neutral interactions, a more rigorous treatment of the divertor plasma using a kinetic model is required.

Purposes of this paper are to examine impurity retention in the divertor chamber with expanding magnetic field and to indicate the important role of charge-exchange process to reducing power flow to the divertor plates on the base of a kinetic theory.

2. Impurity retention in the divertor

2.1. Model and plasma-sheath equation

We consider a simple field-strength profile $B(x)$ of expanding magnetic field in the divertor chamber as sketched in Fig. 1. A spatially varying magnetic field may provide a formation mechanism for an electrostatic potential drop in a flowing plasma. The kinetic equation of cold ions in the source region is simply described by

$$\sigma v_{\parallel}(x, \varepsilon, \mu) \frac{\partial f_{c}(x, \varepsilon, \mu, \sigma)}{\partial x} = S_{c}(x, \varepsilon, \mu) - v_{\parallel}(x, \varepsilon, \mu) \frac{f_{c}(x, \varepsilon, \mu, \sigma)}{\lambda_{cx}}, \tag{1}$$

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PII S0022-3115(96)00524-7

using the energy $\varepsilon = 1/2Mv^2 + e\phi$), the magnetic moment $\mu = 1/2Mv_\perp^2/B$ and the direction of the motion $\sigma = \pm 1$ [5]. Coulomb collisions are neglected on the assumption of $\lambda_c \gg \lambda_{cx}$, L, where λ_c and λ_{cx} are the mean free paths for Coulomb scattering and charge exchange, respectively. The particle source of cold ions produced by ionization and by charge exchange is given by

$$S_c(x,\varepsilon,\mu) = \left(\Gamma_{ic} + \Gamma_0\frac{l_s}{\lambda_{cx}} + \Gamma_{ic}\frac{x-x_s}{\lambda_{cx}}\right) \times \frac{B(x)/B_0}{l_s}\frac{M^2}{4\pi(kT_c)^2}v_\parallel(x,\varepsilon,\mu)\exp[-(\varepsilon - e\phi(x))/kT_c],$$
$$x_s \le x \le L, \tag{2}$$

where Γ_{ic} is the total particle flux of cold ions produced by ionization and Γ_0 is that of ions escaping from the main chamber. The flowing plasma must satisfy the generalized Bohm criterion at the magnetic throat for formation of a stationary continuous potential and a monotonical potential profile can build up only if the Bohm criterion is marginally satisfied at the throat [6]. We can point out possibility of shock-wave excitation in the source-free region where the plasma flow can be supersonic. But, the non-stationary phenomenon and its effect on the transport are beyond the scope of the present analysis. The distribution function of the flowing ions at the magnetic throat is given by a bi-temperature cut-off Boltzmann distribution with temperatures $T_\perp$ and $T_\parallel$ and cut-off energy ε_c such that only ions with $v_\parallel > (2\varepsilon_c/M)^{1/2}$ are left. The flowing ion density is expressed as a function of the magnetic field strength $B(x)$ and the potential $\phi(x)$ [6]. For electrons, we take a Boltzmann distribution with temperature T_e:$n_e(x) = n_0\exp(e\phi(x)/kT_e)$.

The distribution function of cold ions is obtained by integrating the kinetic equation along particle trajectories in the same manner as described in Refs. [5,7]. The cold ion density is expressed in an integral form with respect to x after integration of $f_c(x,\varepsilon,\mu,\sigma)\partial(v_\perp^2, v_\parallel)/\partial(\varepsilon,\mu)$ over the ε-$-\mu$ space. Substituting particle densities into Poisson's equation, we obtain the following integro-differential equation called plasma-sheath equation:

$$\lambda_{D0}^2\frac{e}{kT_e}\frac{d^2\phi}{dx^2} = -\left\{\frac{n_h(\phi(x),B(x))}{n_0}g(x,x_s) + \left(\frac{\pi M}{2kT_c}\right)^{1/2}\frac{1}{n_0}\int_{x_s}^{L}dx' \times \left(\Gamma_{ic} + \Gamma_0\frac{l_s}{\lambda_{cx}} + \Gamma_{ic}\frac{x'-x_s}{\lambda_{cx}}\right)\right.$$
$$\left.\times\frac{B(x')/B_0}{l_s}I(x,x') - \exp\left(\frac{e\phi(x)}{kT_e}\right)\right\} \tag{3}$$

where

$$g(x,x_s) = \begin{cases} 1, & x < x_s, \\ \exp\left(-\dfrac{x-x_s}{\lambda_{cx}}\right), & x_s < x < L, \end{cases}$$

and

$$I(x,x') = \begin{cases} \left\{\exp\left(\dfrac{e(\phi(x')-\phi(x))}{kT_c}\right)\operatorname{erfc}\left[\left(\dfrac{e(\phi(x')-\phi(x))}{kT_c}\right)^{1/2}\right] \right. & \\ \quad -\left(\dfrac{B(x')-B(x)}{B(x')}\right)^{1/2}\exp\left(\dfrac{B(x')}{B(x')-B(x)}\dfrac{e(\phi(x')-\phi(x))}{kT_c}\right) & \\ \quad \left.\times\operatorname{erfc}\left[\left(\dfrac{B(x')}{B(x')-B(x)}\dfrac{e(\phi(x')-\phi(x))}{kT_c}\right)^{1/2}\right]\right\} & \\ \quad \exp\left(-\dfrac{x-x'}{\lambda_{cx}}\right), & x' < x, \\ \exp\left(\dfrac{e(\phi(x')-\phi(x))}{kT_c}\right), & x' > x. \end{cases}$$

Here, we neglected the loss term $-v_\parallel f_c/\lambda_{cx}$ in Eq. (1) in the region $x < x'$ because the length Δx of particle trajectories for $\sigma = -1$ in the source region is much smaller than l_s when $T_c \ll T_e$. Eq. (1) with the source Eq. (2) satisfies particle conservation under the charge-exchange collision if the loss term in the region $x < x'$ is neglected. Eq. (3) has seven parameters: Γ_{ic}/Γ_0, l_s/λ_{cx}, $B_0/B(L)$, $T_\perp/T_e$, $T_\parallel/T_e$, ε_c/kT_e, T_c/T_e and λ_{D0}/L, where λ_{D0} is the Debye length at $x = 0$. The effect of oblique magnetic field is not taken into account in the present analysis. Although oblique magnetic field induces change of particle orbit and plasma current in the narrow region near the divertor plate [8,9], it does not alter the

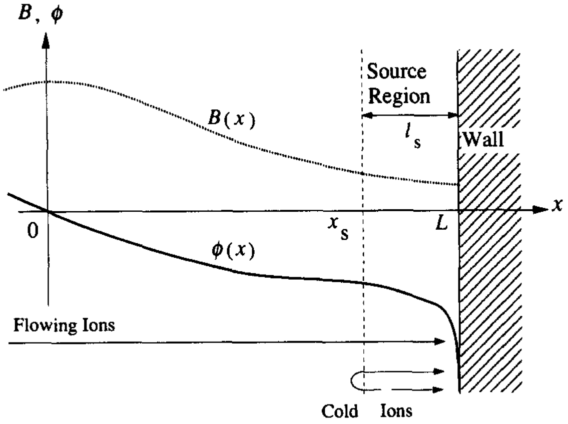

Fig. 1. One-dimensional model of the high-recycling divertor with expanding magnetic field.

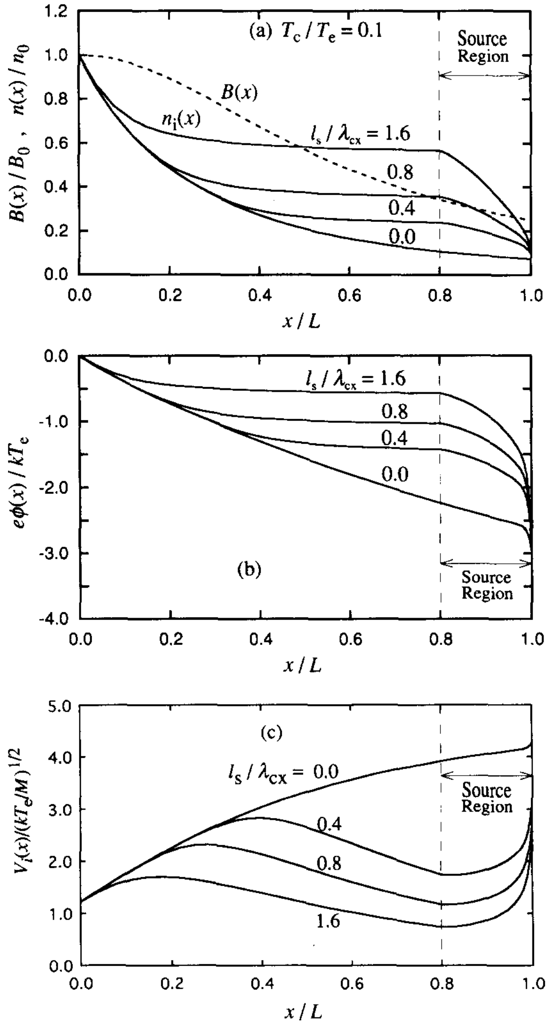

Fig. 2. Spatial profiles of (a) ion density $n_i(x)$, (b) potential $\phi(x)$ and (c) plasma flow velocity $V_i(x)$ along the magnetic field lines for various values of l_s / λ_{cx} where $\Gamma_{ic} / \Gamma_0 = 0$. Parameters of the flowing ions are $T_\perp = 10\ T_c$, $T_\parallel = T_e$, and $\varepsilon_c = 0.187\ kT_e$.

total potential drop and the power transmission factor in the divertor as long as the mean-free path λ_{cx} is much longer than ion gyroradius.

2.2. Results of numerical calculation

Eq. (3) can be solved numerically by transforming it into a set of finite difference equations. The value of ϕ at the throat is defined to be zero and the one at the wall is determined from the ambipolarity of particle fluxes. In order to clarify effects of charge-exchange collisions, we first solve Eq. (3) for various values of the mean free path λ_{cx}, neglecting ionization.

Results are shown in Fig. 2a, b, c. The electrostatic potential drop is formed in the plasma flowing along expanding magnetic field. Fig. 2b, c indicate that the potential drop and the mean plasma velocity $V_i(x)$ decreases in the source-free region with increasing l_s/λ_{cx} because of trapping of cold ions. The plasma momentum is removed along field lines by charge-exchange collisions, but the mean flow velocity increases in the source region so that the Bohm criterion can be satisfied at the sheath edge. The potential drop in the source-free region decreases to zero and part of the cold ions flow into the main chamber through the throat when the cold ion density at the entrance of source region exceeds the flowing ion density at the throat. In this case, trapping of cold ions by the electrostatic potential cannot be expected in the divertor chamber. The upper limit of l_s/λ_{cx} or of Γ_{ic} increases linearly with the mirror ratio $R_L \equiv B_0/B(L)$. A large potential drop in the source region, which is proportional to a value of l_s/λ_{cx}, is formed so as to overcome friction force caused by charge-exchange collisions.

Profiles of the total ion density $n_i(x)$, flowing ion density $n_f(x)$ and cold ion density $n_c(x)$ are shown in Fig. 3. Cold fuel ions and impurity ions produced in the divertor chamber are reflected and accelerated towards the divertor plate by the electrostatic potential. They cannot flow back into the main chamber.

3. Power exhaust by charge-exchange collisions

Charge-exchange collisions reduce the kinetic energy of ions by transferring it to the neutral gas. Each cold ion arriving at the wall carries its initial kinetic energy plus the energy $e(\phi(x)-\phi_w)$ and each electron striking the wall transmits on average an energy of $2kT_c$. Then, the power transmission factor of the divertor plasma defined by $\delta \equiv (Q_e+Q_f+Q_c)/(kT_e(\Gamma_0+\Gamma_{ic}))$ is

$$\delta = 2 + \left\{ \left(\frac{T_\perp}{T_e} + \frac{1}{2}\frac{T_\parallel}{T_e} + \frac{\varepsilon_c}{kT_e} - \frac{e\phi_w}{kT_e} \right) \Gamma_0 \exp(-l_s/\lambda_{cx}) + \int_{x_s}^{L} \left[2\frac{T_c}{T_e} + \frac{(e\phi(x') - e\phi_w)}{kT_e} \right] \right.$$
$$\left. \times \left(\Gamma_{ic} + \Gamma_0 \frac{l_s}{\lambda_{cx}} + \Gamma_{ic} \frac{x'-x_s}{\lambda_{cx}} \right) \exp\left(-\frac{L-x'}{\lambda_{cx}} \right) \mathrm{d}x' \right\} (\Gamma_0 + \Gamma_{ic})^{-1}. \qquad (4)$$

The potential profile $\phi(x)$ is obtained from numerical solution of Eq. (3) and the wall potential ϕ_w is determined from ambipolarity of particle fluxes, $\Gamma_0 + \Gamma_{ic} = \Gamma_e$. Higher energy electrons are supplied from the upstream region of the throat. All electrons produced by ionization are assumed to flow back into the main plasma.

Fig. 4 shows variation of δ with l_s/λ_{cx} for various values of Γ_{ic}. This result indicates that charge-exchange collisions play an important role to reduce heat flow reaching the divertor plates. Replacement of flowing ion by cold ions reduces the

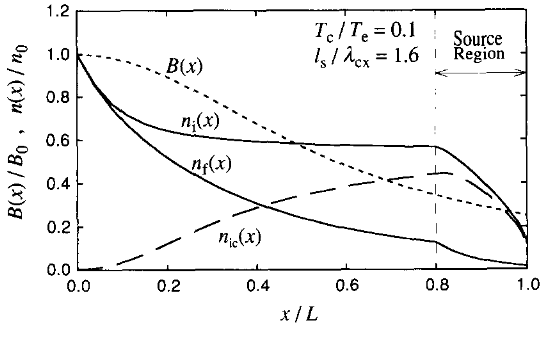

Fig. 3. Spatial profiles of total ion density $n_i(x)$, flowing ion density $n_f(x)$ and cold ion density $n_c(x)$ for $l_s/\lambda_{cx} = 1.6$.

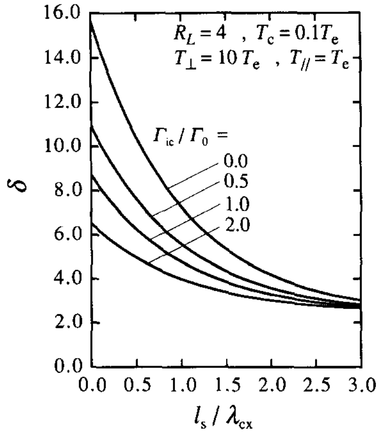

Fig. 4. Variation of the power transmission factor δ with l_s/λ_{cx} for various values of Γ_{ic}/Γ_0, where $R_L = 4$.

ion impact energy at the divertor plate to a small value markedly. The ion impact energy approaches to $1/2\ kT_e + e\Delta\phi$ and the value of δ comes nearer to $5/2 + e\Delta\phi/kT_e$ when l_s/λ_{cx} becomes large, where $\Delta\phi$ is the potential drop in the sheath. Ionization does not contribute to power exhaust, but the value of δ decreases with increasing Γ_{ic} due to amplification of the particle flux and due to decrease of the total potential drop, $-\phi_w$. A similar tendency as indicated in Fig. 4 was observed in the JT-60U tokamak experiment, see Fig. 20 of Ref. [3].

4. Conclusions

A kinetic analysis has been carried out to study impurity retention in the divertor chamber with expanding magnetic field and a role of neutral-gas collisions to reducing power on the divertor plates. The spatial variation of magnetic field strength causes an electrostatic potential drop along the magnetic field lines, which decreases with increasing plasma–neutral collision frequency. Cold ions of fuel and ionized impurities are successfully trapped in the divertor chamber by the electrostatic potential if cold ion density at the source region does not exceed flowing ion density at the magnetic throat. Charge exchange replaces energetic ions by cold ions and the amplified particle flux by ionization reduces the total electrostatic potential drop. Consequently, plasma–neutral collisions markedly reduce the ion heat flow reaching the divertor plates. Low values of the power transmission factor as low as 2- – 3 measured in tokamak experiments can mainly be due to reduction of ion energy through plasma–neutral interaction processes in the divertor.

One of the authors, K.S. thanks Professor Ohyabu of NIFS for the stimulating interest in this work. This research is partially supported by the Grant-in-Aid program of the Ministry of Education and Culture of Japan.

References

[1] G.A. Emmert and A.W. Bailey, J. Nucl. Mater. 93–94 (1980) 238.
[2] A.H. Futch, G.F. Matthews, D. Buchenauer, D.N. Hill, R.A. Jong and G.D. Porter, J. Nucl. Mater. 196–198 (1992) 860.
[3] N. Asakura, K. Shimizu, N. Hosogane, K. Itami, S. Tsuji and M. Shimada, Nucl. Fusion 35 (1995) 381.
[4] K. Sato and H. Katayama, J. Nucl. Mater. 220–222 (1995) 501.
[5] K. Sato, F. Miyawaki and W. Fukui, Phys. Fluids B 1 (1989) 725.
[6] K. Sato, H. Katayama and F. Miyawaki, J. Phys. Soc. Jpn. 61 (1992) 3034.
[7] G.A. Emmert et al., Phys. Fluids 23 (1980) 803.
[8] R.H. Cohen and D.P. Ryutov, Phys. Plasma 21 (1995) 2011.
[9] H. Claassen and H. Gerhauer, Contrib. Plasma Phys. 36 (1996) 381.