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Influence of the Wall Material on the H-mode Performance

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Abstract

Theory on the influence of the wall materiel on the level of the enhanced confinement in H-mode is discussed. When the high-Z material is employed as the wall, the reflection of the neutral particles causes the higher neutral particle density in the plasma. The increased neutral particles lead to the loss of the ion momentum, decrease the radial electric field and degrade the confinement improvement.

Key words: H-mode, neutral particles, radial electric field, charge exchange loss, wall reflection, high-Z material, low-Z material

It is well known, from various experiments, that the property of the H-mode plasma [1] depends on the wall materials [2]. General observation is that the improvement of the energy confinement τ_E over that of the L-mode is higher when the wall material is composed of the low-Z material (Z being the ionic number). It is also known that the threshold power for the H-mode transition is lower for the case of low-Z wall. The features of the edge localized modes (ELMs) [3] are also different. The understanding of the difference of the improved confinement modes under the various wall materials is not only a challenge in the confinement physics, but also is an inevitable issue from the view point of the design of the future stationary-burning plasma. This is because the choice of the wall material would be strongly regulated in such devices from the engineering considerations (such as the persistence to the high heat flux or to the radio activation), and because the difference in the plasma performance crucially influences the design point of the system. In spite of these importance, there was no model to explain these dependencies.

In this article, we theoretically study the influence of the wall material based on our model of the H-mode, i.e., the radial electric field bifurcation model [4]. The neutral density in the core plasma, which tends to reduce the radial electric field [5], is predicted to be enhanced in the case of high-Z wall. This explains the reduction of the enhancement factor in the high-Z wall.

The theory of the H-mode based on the radial electric field bifurcation [4] is extended in various manner and is now widely accepted as a possible mechanism to explain the H-mode phenomena [6]. The development of the radial electric field, E_r, is governed by the equation

$$\frac{1}{e}\varepsilon_\perp\varepsilon_0\frac{\partial E_r}{\partial t} = \Gamma_{e-i}^{ano} - \Gamma_i^{lc} - \Gamma_i^{bv} - \Gamma_i^{cx} - \Gamma_i^{others} \qquad (1)$$

where $\varepsilon_\perp$ and ε_0 are the perpendicular susceptibility and vacuum susceptibility. The radial fluxes have several origins. The excess electron flux by anomalous transport is the first in the right hand side [4], and super scripts lc, bv and cx denote the ion flux due to the loss cone loss [4], by the bulk viscosity [7] and by the charge exchange [5]. Other mechanisms have been discussed [8], however, they are combined as others, because the argument of the article is not changed by them qualitatively.

By balancing the first and second terms in the right hand side of Eq.(1), the bifurcation of radial electric field is predicted at particular pressure gradient at edge. The bifurcation is also found by balancing the second and third terms, although the threshold gradient has slight deference. The presence of the neutral particles in the plasma causes the drag force on ions due to the loss of momentum by the charge exchange appears [5]. It was found that the loss rate in the good confinement state increases as the neutral density n_0 increases. As the neutral density exceeds a threshold value $n_{0,c}$,

$$n_0 > n_{0,c} \tag{2}$$

the hard transition is prohibited and a soft transition takes place [5]. If n_0 is increased more, even the slow and soft transition becomes impossible. The order of magnitude estimate for $n_{0,c}$ was given

$$n_{0,c} \simeq \frac{\nu_i}{<\sigma_{cx} v>} \frac{\rho_p}{\Delta_n} \tag{3}$$

where ν_i is the ion collision frequency, ρ_p is the ion poloidal gyro radius, σ_{cx} is the charge-exchange cross section and Δ_n is the penetration length of the neutral particles in the core. This result explains the experimental knowledge that the energy confinement of the H-mode is degraded by the neutrals in the plasma [9]. (See ref.[5] for details.)

Now we discuss the influence of the wall material on the neutral density. Figure 1 illustrates the flow of particles near the edge. The wall reflection is known as an important source of neutrals in the core, and we here consider the neutrals of such origin. In reality, the neutrals come also from the private region of the divertor plasma. The extension of the present study to add such a contribution is possible.

The screening of neutrals in the scrape-off-layer (SoL) is the key for the penetration, and the penetration probability of neutrals from the wall into the plasma, p, is evaluated as

$$p = \exp\left(-\int ds \, \frac{n_e <\sigma_{ion} v>}{v_0}\right) \tag{4}$$

where the integral is taken along the path of neutrals across the SoL, v_0 denotes the neutral velocity, and σ_{ion} indicates the ionization cross section. The in-coming neutral flux into the plasma is given as

$$\Gamma_n^{in} = \int_0^\infty dv_0 \, p(v_0) \Gamma_{wall}(v_0) \tag{5}$$

Since the probability p has a strong dependence on the initial velocity, one must consider the multiple energy component from the wall. In order to show an analytic study, we take two components, the slow part, Γ_{wall}^s, and the fast one Γ_{wall}^f. They are characterized by the average velocity V_s and V_f as is shown in Fig.2. In a more quantitative study, the former is contributed from such particles as Frank-Condon particle, and the latter comes from reflection. By this simplification we write

$$\Gamma_n^{in} = p(V_s)\Gamma_{wall}^s + p(V_f)\Gamma_{wall}^f \tag{6}$$

The outward neutral flux, Γ^{out}, has characteristic energy E_{out}, which is determined by the ion temperature at the neutral penetration distance. The inward neutrals are either ionized or subject to charge exchange. Considering the branching ratio of these two processes, and taking into account of the outward neutral flux due to the recombination process, Γ^{recom}, we have

$$\Gamma^{out} = \frac{<\sigma_{cx} v> n_i}{<\sigma_{cx} v> n_i + <\sigma_{ion} v> n_e} \Gamma_n^{in} + \Gamma^{recom} \tag{7}$$

The relation between the outward flux Γ^{out} and the flux leaving the wall are combined through the recycling coefficient and the reflection coefficient. We symbolically write

$$\Gamma^{s}_{wall} = R_s \Gamma^{out} \tag{8}$$

and

$$\Gamma^{f}_{wall} = R_f \Gamma^{out} \tag{9}$$

where R_s is the recycling coefficient and R_f is the reflection coefficient. There is of cause a contribution of the plasma flux onto the wall. This is neglected here for the transparency of the analysis.

From these relations we have the amplification of the neutral flux as

$$\Gamma^{out} = \frac{1}{1 - \frac{<\sigma_{cx} v> n_i}{<\sigma_{cx} v> n_i + <\sigma_{ion} v> n_e}(p(V_s)R_s + p(V_f)R_f)} \Gamma^{recom} \tag{10}$$

and

$$\Gamma^{in}_{n} = \frac{p(V_s)R_s + p(V_f)R_f}{1 - \frac{<\sigma_{cx} v> n_i}{<\sigma_{cx} v> n_i + <\sigma_{ion} v> n_e}(p(V_s)R_s + p(V_f)R_f)} \Gamma^{recom} \tag{11}$$

The neutral density is evaluated by introducing the life-time τ_n,

$$\tau_n = \frac{1}{<\sigma_{cx} v> n_i + <\sigma_{ion} v> n_e} \tag{12}$$

as

$$n_0 = \tau_n \Gamma_n^{in} / \Delta_n \tag{13}$$

Since the screening effect by the SoL plasma has exponential dependence on the initial neutral velocity leaving the wall, $p(V_f)$ is much larger than $p(V_s)$. The fast particles penetrate deeper and give a larger value of E_{out}, which again causes larger $p(V_f)$. For the simplicity we assume $p(V_f)R_f >> p(V_s)R_s$, and have

$$n_0 = \frac{p(V_f)R_f}{<\sigma_{ion}v>n_e + <\sigma_{cx}v>n_i\,(1 - p(V_f)R_f)}\,\frac{\Gamma^{recom}}{\Delta_n} \tag{14}$$

Introducing the thickness of the layer of recombination, Δ_{recom}, the flux Γ^{recom} is expressed as $\Gamma^{recom} = <\sigma_{recom}v>n_e n_i \Delta_{recom}$, where σ_{recom} is the recombination cross-section. Substituting this expression in Eq.(14), we have

$$n_0 = p(V_f)R_f\,\frac{<\sigma_{recom}v>n_e n_i}{<\sigma_{ion}v>n_e + <\sigma_{cx}v>n_i\,(1 - p(V_f)R_f)}\,\frac{\Delta_{recom}}{\Delta_n} \tag{15}$$

Note that this is the lower bound for the neutral density.

These results clarify that, as the reflection coefficient or the initial velocity V_f increases, the neutral density in the plasma increases, and thus deteriorates the H-mode performance. Combining Eqs.(3) and (15), we see the upper bound for the penetration probability in order to have the sharp L-to-H transition as

$$p(V_f)R_f < \frac{<\sigma_{ion}v>n_e + <\sigma_{cx}v>n_i}{<\sigma_{recom}v>n_e + v_i\rho_p/\Delta_{recom}}\,\frac{v_i}{<\sigma_{cx}v>n_i}\,\frac{\rho_p}{\Delta_{recom}} \tag{16}$$

This expression explains, at least qualitatively, the influence of the metal wall on the H-mode performance. The reflection coefficient is larger when the target is high-Z material. The energy reflection coefficient is larger for high-Z material, too. Both mechanisms lead to the higher values of $p(V_f)R_f$. The neutral density is higher in the plasma, assuming that the plasma condition is common. This is the reason for the slight degradation of the H-mode confinement in the wall of high-Z materials.

The reflection coefficient was given for incident ions as a function of the reduced energy (normalized energy), W, in the study on the plasma wall interactions. The formula gives an insight for the reflection coefficient. The explicit form of the reduced energy is given as [10]

$$W = 32.5 \frac{M_2}{M_1 + M_2} \frac{1}{Z_1 Z_2 \left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2}} E(\mathrm{keV}) \qquad (17)$$

where M and Z are mass and atomic numbers, and the suffix 1 denotes the incident ion and 2 denotes the target atom, and E is the energy of incident particle measured in keV. If W is above unity, the refection coefficient decreases rapidly. If W is blow unity it approaches to unity. From this relation, we see that the Z_2 dependence is very important in comparing the high-Z material and low-Z material. The reduced energy is low in the high-Z wall, giving the large reflection coefficient and energy reflection coefficient.

The experimental study on the influence of the wall materials on the neutral energy distribution was done in TEXTOR device [11]. The cases of the iron and carbon were compared. The existence of the fast and reflected neutrals was confirmed in the case of the iron.

In this article, we present a theoretical model of the influence of the wall material on the performance of the H-mode. The reflection coefficient, screening by the SoL, and the neutral density in the core are the key for the mechanism. The higher energy component in the reflected neutrals, in the case of high-Z wall, impedes the radial electric field formation and degrades the confinement of the H-mode. This model also provides a possibility to overcome the deterioration of the confinement in the high-Z wall by the pumping. This model also provides one of the reasons for the difference between hydrogen plasma and deuterium plasma. In the case of hydrogen, the velocity of neutrals, v_0, is faster than deuterium due to the lighter mass. This may allow the penetration of neutrals into the plasma more easily for the case of hydrogen plasmas.

The isotopic effect of the confinement was explained in terms of the difference in the anomalous transport coefficient χ. The impurity can also change the transport coefficient, since the formula for χ was given to have the dependence $\gamma \propto \sqrt{Z/M}$ [12]. Therefore the high effective Z-value tends to enhance the transport coefficient. This process can also be cooperative in influencing the H-mode performance.

This model will provide a basis for the quantitative study through numerical simulations. Atomic processes are simplified here, but extension is possible to complete them. Also important is the precise measurement of the neutral behaviour, for which some of examples were given [11]. The data in the case of the H-mode and other improved confinement modes would be necessary. The validation of the model is left for the future study, in which numerical result will be compared to the experimental observation.

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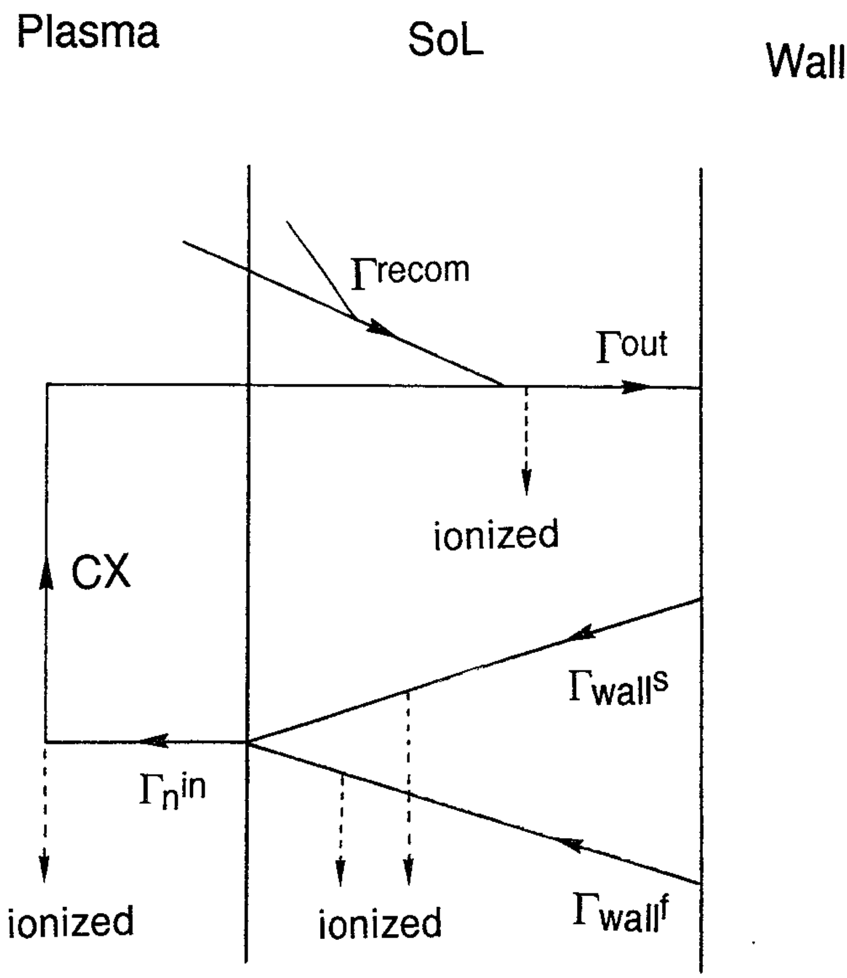
Figure Captions

Fig. 1 Flow of neutral particles near the plasma boundary and the wall.

Fig.2 Schematic velocity distribution of the neutral particles leaving from the wall.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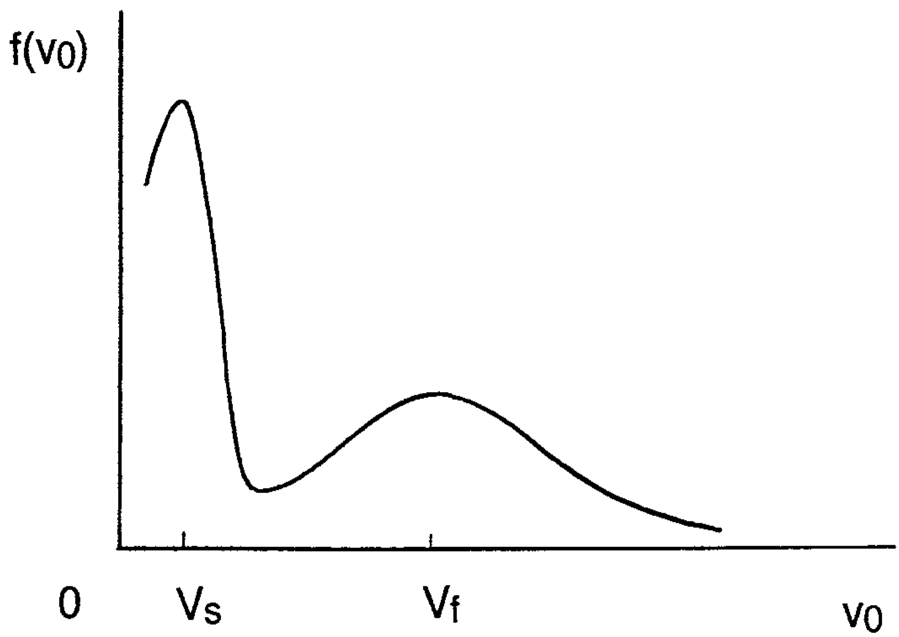
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