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Neutral particle transport under strong hydrogen recycling condition in the GAMMA 10 central cell

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Abstract

In order to understand the behavior of neutral hydrogen in ICRH plasmas of the GAMMA 10 tandem mirror, we tried new simulations of neutral transport by using the DEGAS Monte Carlo code in which the effects of hydrogen recycling were taken into account. This simulation has been performed by introducing a multiplication coefficient in DEGAS to control the amount of desorbed test particles, which enables us to simulate the neutral transport for the first time under the conditions in which the recycling coefficient exceeds unity. By using the multiplication coefficient, it was found that the axial profile of the atomic hydrogen density obtained from the simulation changed significantly. On the other hand, there is little influence on the radial profile of the simulated hydrogen density. The simulation result, taking the axial variation of the multiplication coefficient into consideration, well predicted the result of the H_α-emission measurements. This indicates that strong hydrogen recycling is localized near the midplane. These calculation results are discussed from the view point of the wall-reflux coefficient deduced from the DEGAS simulation. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

In magnetic fusion devices, recycling from the vacuum wall plays an important role in attainment of good plasma confinement. A combination of Balmer-line emission measurement and neutral particle transport simulation has been used in order to investigate the hydrogen behavior in plasma–surface interactions [1–3].

In the GAMMA 10 tandem mirror [4], recycling mechanisms including particle reflection and gas desorption have been investigated quantitatively by using pressure-balance equations along with ‘plasma pumping’ which was one of the essential characteristics in open-ended systems [5,6]. The plasma pumping is a phenomenon of the charged particle transport from a central region to both end regions along the magnetic field line. A numerical model calculation based on atomic and molecular processes also has been used for studying the gas recycling [7]. It has been found that the recycling coefficient, i.e. number of particles reflected and desorbed from a wall per particle incident on the wall, increased with the ion temperature at the central cell midplane [5,7]. The DEGAS [9] neutral transport simulation has been applied to GAMMA 10 plasmas [5,8]. The radial distribution of the hydrogen density calculated from DEGAS agreed well with the radial distribution of the H_α-emission intensity measured at the midplane [5]. In ion cyclotron resonance heating (ICRH) plasmas of GAMMA 10 [4,10], however, it has been observed that the axial profile of the H_α intensity pre-

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dicted from DEGAS, disagreed with the H_α-emission measurements along the magnetic field line [8]. It has been speculated that this discrepancy between the simulation and the measurements may be ascribed to the effect of the strong hydrogen recycling. Hence, it is an urgent subject to simulate the neutral particle transport under the actual experimental conditions in order to understand the behavior of neutral hydrogen along the magnetic field.

We have performed new simulations of neutral transport with the DEGAS code for the first time under conditions in which the recycling coefficient exceeded unity. In this paper, we describe the neutral particle simulation including the effect of the strong hydrogen recycling as compared with the H_α-emission measurements.

2. Modeling

In ICRH plasmas of GAMMA 10, the neutral particles originating from both gas puffing and hydrogen recycling can easily penetrate into the main plasma because of the low electron density ($\sim 10^{12}$ cm^{-3}). Charge exchange (CX) neutral particles produced in the plasma have longer mean free paths due to high ion temperatures (several keV) [10] and escape from the plasma and hit the wall surface. Such high-energy neutrals play an important role in the plasma-wall interactions in GAMMA 10. When CX neutrals impinge on the vacuum vessel wall, the incident particles reflect and return to the plasma, or cause gas desorption from the wall. The recycling coefficient γ can be determined from pressure-balance equations based on dynamic pressure measurements [5,7], as follows:

$$\gamma = \frac{\text{reflected atoms} + \text{desorbed molecules} \times 2}{\text{energetic incident atoms}} \qquad (1)$$
$$= R_N + R_D,$$

where R_N and R_D are particle reflection and desorption coefficients, respectively [5,7]. We refer to the Eckstein and Verbeek model for the reflection coefficient [11]. It has been observed that the recycling coefficient was more than unity in the ion temperature range of our ICRH plasmas. In standard ICRH plasmas of GAMMA 10, the plasma duration is about 100–200 ms. Thus it is quite within the bounds of possibility that the recycling coefficient exceeds unity under the plasma parameters.

The DEGAS neutral transport code is a 3-dimensional multiple species neutral transport code using the Monte Carlo method [9]. The DEGAS code has been modified to take into account the dissociative–excitation reactions of hydrogen molecules [5,12]. In this paper, we used this modified DEGAS code and refer to the modified DEGAS as the standard DEGAS. Fig. 1(a) and (b) illustrate the plasma mesh model of the GAMMA 10 central cell and the spatial profile of the electron density used in the simulation code, respectively. This mesh model was designed assuming axisymmetry of the vacuum vessel, RF antennae (Double Half-Turn antenna, Nagoya Type-III antenna [13]) and gas puffers. As shown in Fig. 1(a), the H_α-emission detectors are installed in the GAMMA 10 central cell along the magnetic field line [8]. In this calculation, test particles are launched from a segment representing the gas puffer in the central cell mirror throat region (GP#3). We neglect the contribution of the gas puffing from the gasbox, since gas puffer #1b (GP#1b) is used for the startup of the ICRH plasma by injecting hydrogen gas from the gasbox with a short pulse ($\sim$10 ms). The electron density profile was determined from the experimental data measured by the microwave interferometers located at the midplane and mirror throat. The radial profile of the electron temperature in the mirror throat region was determined on the assumption that the electron temperature profile measured at the midplane can be projected along the magnetic field line.

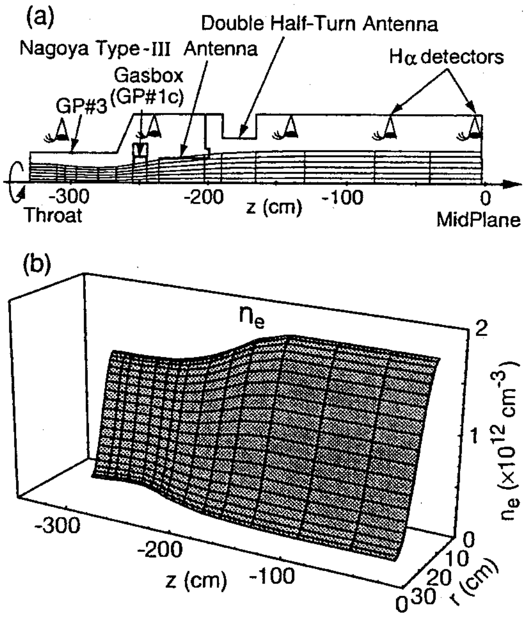

Fig. 1. Mesh model of the GAMMA 10 central cell used in the DEGAS simulation (a), and spatial profile of the electron density (b).

In the standard DEGAS code, the recycling coefficient has been treated as unity (i.e. $1 = R_N + R_D^{DEGAS}$). In order to control the amount of the desorbed test particles from the wall, we introduced the multiplication coefficient α for desorbed particles as follows

$$R_D = \alpha R_D^{DEGAS}. \qquad (2)$$

This multiplication coefficient enables us to simulate the neutral particle transport with DEGAS under conditions in which the recycling coefficient exceeds unity.

3. Calculation results

We carried out the neutral particle simulation under strong recycling conditions by using the multiplication coefficient α for the desorbed molecules. Fig. 2 shows the calculated radial density profiles of the hydrogen atoms at the mirror throat region ($z = -307$ cm), near the gasbox ($z = -240$ cm) and at the midplane ($z = 0$ cm). The profiles of calculated hydrogen density were normalized by the number of launched test particles (5×10^{19} molecules s^{-1}) from the gas puffer at the mirror throat (GP#3). The density profile for $\alpha = 1.0$ corresponds to the calculation result with the standard DEGAS code. In the mirror throat region, in which the gas puffer has been installed, the radial profile of the hydrogen density is almost unchanged with the increase of the multiplication coefficient α. Near the gasbox, the atomic hydrogen density increases with the multiplication coefficient without changing the density profile. The tendency that the density increases as the multiplication coefficient becomes large is enhanced at the midplane. This phenomenon may be explained as follows: In the mirror throat region, particle fueling is less influenced by the wall recycling because the gas puffing from GP#3 dominates the fueling. On the other hand, the calculated hydrogen density far from the gas puffer is dominated by the fueling from the wall recycling and depends strongly on the multiplication coefficient α. The fueling from the recycling is uniform in the azimuthal direction, since the vacuum vessel of GAMMA 10 is axisymmetric. It is speculated that the behavior of the neutral penetration in the radial direction of plasma is unchanged. Hence each radial profile of hydrogen density at the midplane is thought to be similar to the other, although the axial profile of atomic hydrogen density significantly changed under the condition that the multiplication coefficient was varied.

The above results were compared with the axial profile of the H_α intensity measured from some H_α-emission detectors located along the magnetic field. Fig. 3 shows the comparison between the axial profile of the H_α intensity observed in the central cell and that predicted from the DEGAS simulation. Each simulation result is fitted to the H_α intensity measured at the mirror

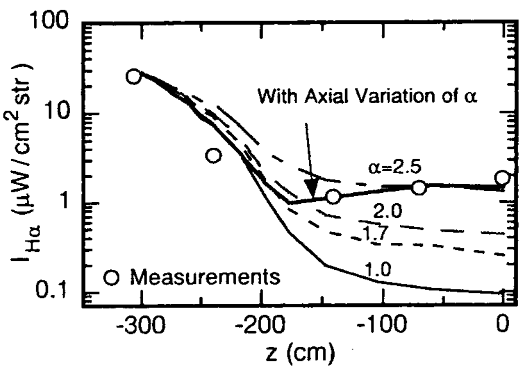

Fig. 3. Axial profile of H_α intensity predicted from the DEGAS code (lines) and the results measured with the H_α-detectors (circles). The simulation results are fitted to the measured data at the mirror throat.

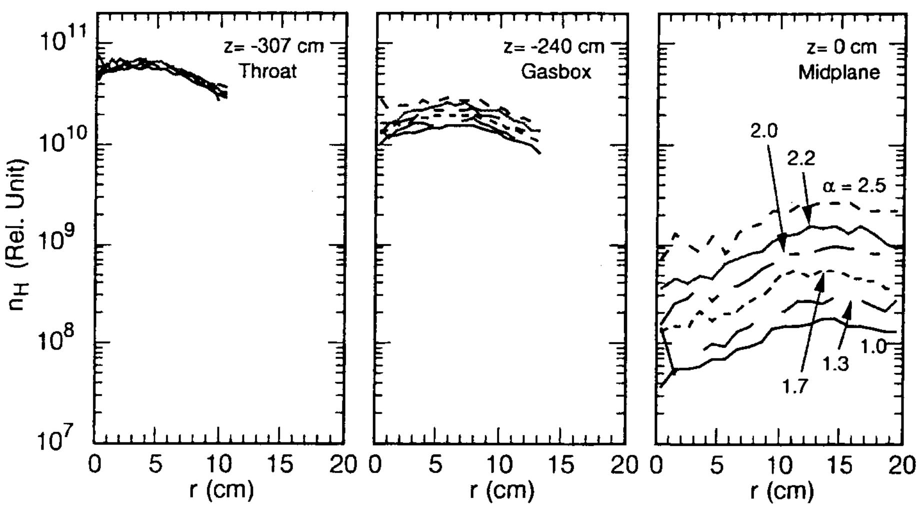

Fig. 2. Radial profiles of atomic hydrogen density calculated from the DEGAS code at the mirror throat, near the gasbox and at the midplane. The DEGAS code takes into account the multiplication coefficient α for the desorbed test particles.

throat. The calculated H_α intensity near the midplane increases with the multiplication coefficient α. In the case of $\alpha = 2.5$, the calculated H_α intensity near the midplane roughly agrees with the measured data. However, the H_α intensity from the simulation outside the midplane region (i.e. -240 cm $< z < -141$ cm) is higher than the measured data. These calculation results will be discussed in Section 4.

4. Discussion

The recycling coefficient shown in Eq. (1) is an index of the global hydrogen recycling estimated from the measurement data. In order to discuss the relationship between the recycling coefficient and the simulation results with the multiplication coefficient α, we defined the wall-reflux coefficient γ^{DEGAS} as follows:

$$\gamma^{\mathrm{DEGAS}} = \frac{\sum w_{\mathrm{Re}} + \sum w_{\mathrm{De}} \times 2}{\sum w_{\mathrm{In}}}, \tag{3}$$

where w_{In}, w_{Re} and w_{De} are the weights of incident, reflected and desorbed test particles obtained from DEGAS, respectively. These weights are summed up over both reflection and desorption at the wall throughout the neutral simulation. In the DEGAS code, the information on the number of the neutral particles is treated as the weight of the test particles. Then, this wall-reflux coefficient can be regarded as a global index of the hydrogen recycling in the overall region of the neutral transport simulation. In Fig. 4, the wall-reflux coefficient γ^{DEGAS} determined from DEGAS is shown as a function of the H_α intensity at the midplane predicted from the simulation using the various multiplication coefficients. The wall-reflux coefficient γ^{DEGAS} is estimated to be 1.8 in the case of $\alpha = 2.5$, which is greater than the recycling coefficient determined from the pressure-balance equations based on the experimental data [5,7]. The overestimation of the wall-reflux coefficient γ^{DEGAS} is ascribed to the axial variation of strength of the hydrogen recycling. It has been found that the ion temperature in ICRH plasmas has a remarkable variation along the magnetic field line [14]. For example, the ion temperatures at the midplane and the mirror throat have been observed to be several keV and few hundred eV, respectively [4,10]. The recycling coefficient evaluated from the pressure-balance equations depends on the ion temperature. It is, hence, speculated that the multiplication coefficient for the desorbed molecules varies along the machine axis.

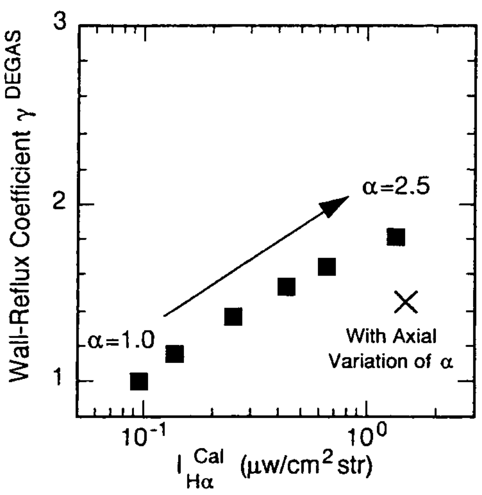

Fig. 4. Wall-reflux coefficient γ^{DEGAS} estimated from the DEGAS code as a function of the calculated H_α intensity at the midplane.

To make the axial variation of the recycling strength clear, we made another attempt to simulate the neutral transport by using axial variation of the multiplication coefficient. A bold solid curve in Fig. 3 shows the axial profile of the H_α intensity deduced from the simulation result, which enables us to explain the measured intensity profile. In this calculation, the multiplication coefficient α near the midplane is given to be more than three and the α outside of the midplane is assigned to be nearly unity, which indicates the strong localization of the hydrogen recycling near the midplane. The wall-reflux coefficient γ^{DEGAS} is determined to be 1.4, which is comparable with the recycling coefficient estimated from the pressure-balance equations. From the above results, it is clarified that the axial profile of the measured H_α intensity can be explained by the DEGAS simulation using the multiplication coefficient for controlling the desorbed test particles. This implies that the amount of hydrogen recycling plays an important role in the simulation of the neutral transport under the strong recycling condition.

5. Conclusion

We attempted successfully to make new simulations of neutral particle transport with the DEGAS code for the first time under the conditions with the recycling coefficient exceeding unity by controlling the desorbed hydrogen molecules in order to explain the experimental results in the GAMMA 10 plasma. We found good agreement between the H_α intensity measurements and the DEGAS simulation using the axial variation of the multiplication coefficient. This result implies the localization of the strong hydrogen recycling near the midplane. The wall-reflux coefficient calculated from DEGAS is consistent with the recycling coefficient determined from the pressure-balance equations. These results suggest that the amount of hydrogen recycling from the vessel wall is important for discussing the neutral particle transport under strong recycling conditions.

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