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Neutral Transport Analysis in Non-axisymmetric Anchor Region of the GAMMA 10 Tandem Mirror Using a Monte-Carlo Simulation

NAKASHIMA Yousuke, HIGASHIZONO Yuta, OHKI Toshikazu, SHOJI Mamoru[1], KOBAYASHI Shinji[2], KUBOTA Yuusuke, YOSHIKAWA Masayuki, ISLAM Md. Khairul, FUKASAWA Takahiro, ISHIMOTO Yuki, WATANABE Kazuhiro, OGITA Takeshi, YAMADA Masaki, MURAKAMI Ryouhei and CHO Teruji

Plasma Research Center, University of Tsukuba, Ibaraki 305-8577, Japan

[1]National Institute for Fusion Science, Toki 509-5292, Japan

[2]Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan

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Abstract

Transport of neutral particles in non-axisymmetric anchor region of the GAMMA 10 tandem mirror is described in terms of a Monte-Carlo simulation and of Hα line-emission measurements. A three-dimensional neutral transport simulation has been performed by applying the DEGAS ver.63 code to the anchor region. A detailed mesh structure was built up for the three-dimensional geometry in this region and the simulation was carried out under a plausible assumption of particle source on experimental data basis. In standard Hot-Ion-Mode plasmas, a series of Hα line-emission measurements have been carried out and axial distribution of particle source rate over the region from the mirror-throat to the anchor-cell is discussed based on both calculation and measurements.

Keywords:

GAMMA 10, tandem mirror, neutral transport, Monte-Carlo simulation, DEGAS code, Hα emission, hydrogen recycling

1. Introduction

Analysis of neutral particle transport is an important issue to understand hydrogen recycling and transport phenomena in the edge plasma regions. It is also important to analyze particle and energy balance for attaining high β plasmas in the tandem mirror devices [1,2]. In the GAMMA 10 tandem mirror, neutral hydrogen density in the central-cell has been estimated by measuring spatial-profiles of Hα line-emission together with neutral transport simulation [2-4]. The neutral density is evaluated from the absolute value of the Hα emissivity based on the collisional-radiative model [5]. The DEGAS Monte-Carlo code [6] has been used for the neutral transport simulation in the GAMMA 10 plasma. The code has been modified to take into account of the effect of dissociative-excitation reaction of molecular hydrogen [2,7].

GAMMA10 is axisymmetric minimum-B anchored tandem mirror with thermal barrier [8]. The device consists of an axisymmetric central-mirror cell, anchor-cells with minimum-B configuration, and plug/barrier cells with axisymmetric mirrors. In the anchor-cell, there exist transition regions where the shape of the magnetic flux tube becomes flat and the cross section of plasma is elongated elliptically. In the transition region, the thickness of the plasma is the same order of the mean free path length of hydrogen molecules and is much shorter than those of Franck-Condon neutrals. Under these circumstances, the behavior of neutrals provides valuable information not only for the tandem mirror research but also for the edge plasma investigation in divertor configurations.

In standard ion-cyclotron-range-of-frequency (ICRF)-heated hot-ion-mode plasmas, fueling experiments using neutral beam injectors (NBIs) have been started for achieving potential confinement of higher density plasmas [9,10]. In these experiments, detailed measurements of Hα line-emission were performed from the central-cell midplane to the outer-transition region of the anchor-cell [11]. In order to evaluate the neutral density profile in non-axisymmetric region, a three-dimensional neutral transport simulation has been started by using the DEGAS ver.63 code [12]. In this paper, we describe the detail of the Monte-Carlo simulation and discuss the location of particle source and its intensity in the non-axisymmetric anchor-cell based on the measured results of Hα line-emission.

Corresponding author's e-mail: nakashma@prc.tsukuba.ac.jp

2. Neutral transport simulation using the DEGAS Monte-Carlo code

2.1 Mesh structure in non-axisymmetric anchor-cell

The DEGAS ver.63 Monte-Carlo code, which is applied to execute the three-dimensional neutral transport simulation in anchor-cell, is modified so as to take the dissociative-excitation of hydrogen molecules into consideration in the neutral transport process in order to make the simulation adapt to the lower density range below 10^{13} cm^{-3}. The mesh model of the wall-surface of the anchor minimum-B region and the surface plot of the plasma grid newly constructed for the simulation are shown in Fig. 1. As shown in the figure, the model introduces a symmetry in vertical direction and the simulation space is divided into 11 segments radially and 8 segments azimuthally. In the axial direction, 41 segments are utilized for the simulation. In this simulation, gas desorption from the movable limiter inserted in the outer-transition region of the anchor-cell is considered together with the particle source from the gas puffer near the mirror throat region.

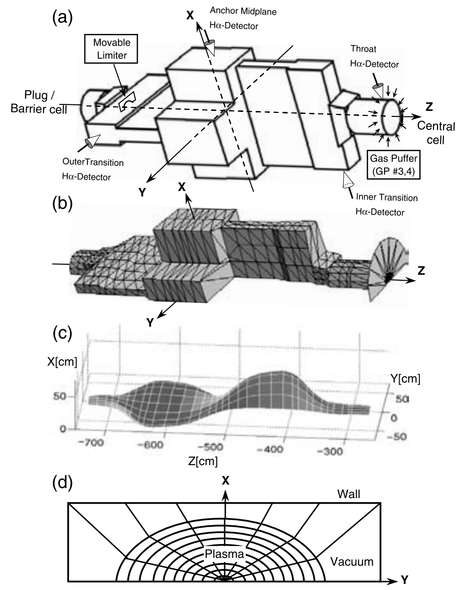

Fig. 1 Mesh model of the anchor minimum-B region used for DEGAS ver.63. (a) schematic view of the vacuum vessel, (b) surface structure of the vessel wall, (c) cross section (x-y plane) of the plasma and the wall, (d) grid shape of the plasma surface.

2.2 Modeling of plasma parameter

Since the obtained plasma parameters from the experiments are practically insufficient for the simulation, an appropriate assumption is required for taking an input dataset into the simulation code. The following two typical models are adopted as electron density profile. The spatial profiles (on y-z plane) of the plasma electron density used for the simulation are shown in Fig. 2. One, as shown in Fig. 2(a), is the density model assuming the flux conservation with collision-less plasma flow in the region where the intensity of magnetic field varies in the axial direction. The other is the uniform density model from the central-mirror throat to the periphery of the anchor midplane, considering the particle trapping effect in the local mirror configuration of anchor transition region as shown in Fig. 2(b). In both models, the density profiles are determined on the basis of the measured data at the central-cell, the mirror throat and the anchor midplane, considering the shape of the magnetic flux tube from the central-cell to the anchor-cell.

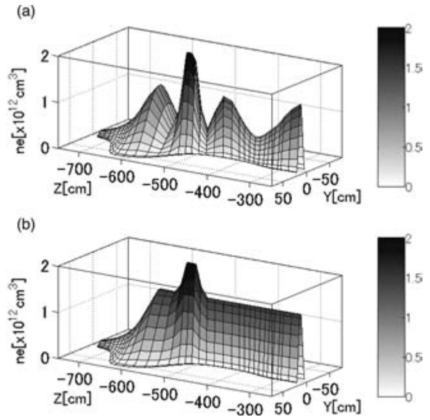

Fig. 2 Spatial profiles (on y-z plane) of the electron density used for the simulation. (a) Collision-less plasma flow model, (b) uniform density model.

3. Simulation results and discussion

3.1 Neutral density profiles in the anchor-cell

Figure 3 shows the 3-D simulation results of neutral hydrogen density profiles. In the anchor midplane, as shown in Fig. 3(a), it is recognized that the molecular hydrogen density radially decreases toward the core region of the plasma and further reduces along with the magnetic field line from the mirror throat ($z = -300$ cm) to the anchor midplane ($z = -520$ cm). Penetration of neutrals is taking place in the edge region where the plasma thickness becomes thin. The result implies that injected hydrogen molecules from the mirror-throat gas puffer are transported to the anchor transition region with significant attenuation and only a small amount of them reaches the anchor midplane.

In contrast to the molecular density, atomic hydrogen density shown in Fig. 3 (b) has a tendency to concentrate in the plasma core region. The atomic density also shows the rather uniform density over the plasma cross section in inner and outer transition regions where the plasma cross section becomes much elongated elliptically. Although these mechanisms are not clarified in detail, longer mean free path of Franck-Condon neutrals compared with the plasma thickness may enhance the production of atomic hydrogen inner region of the plasma column and form such density profiles in the anchor-cell.

3.2 Comparison to the experimental results

Figure 4 shows the comparison between the simulation

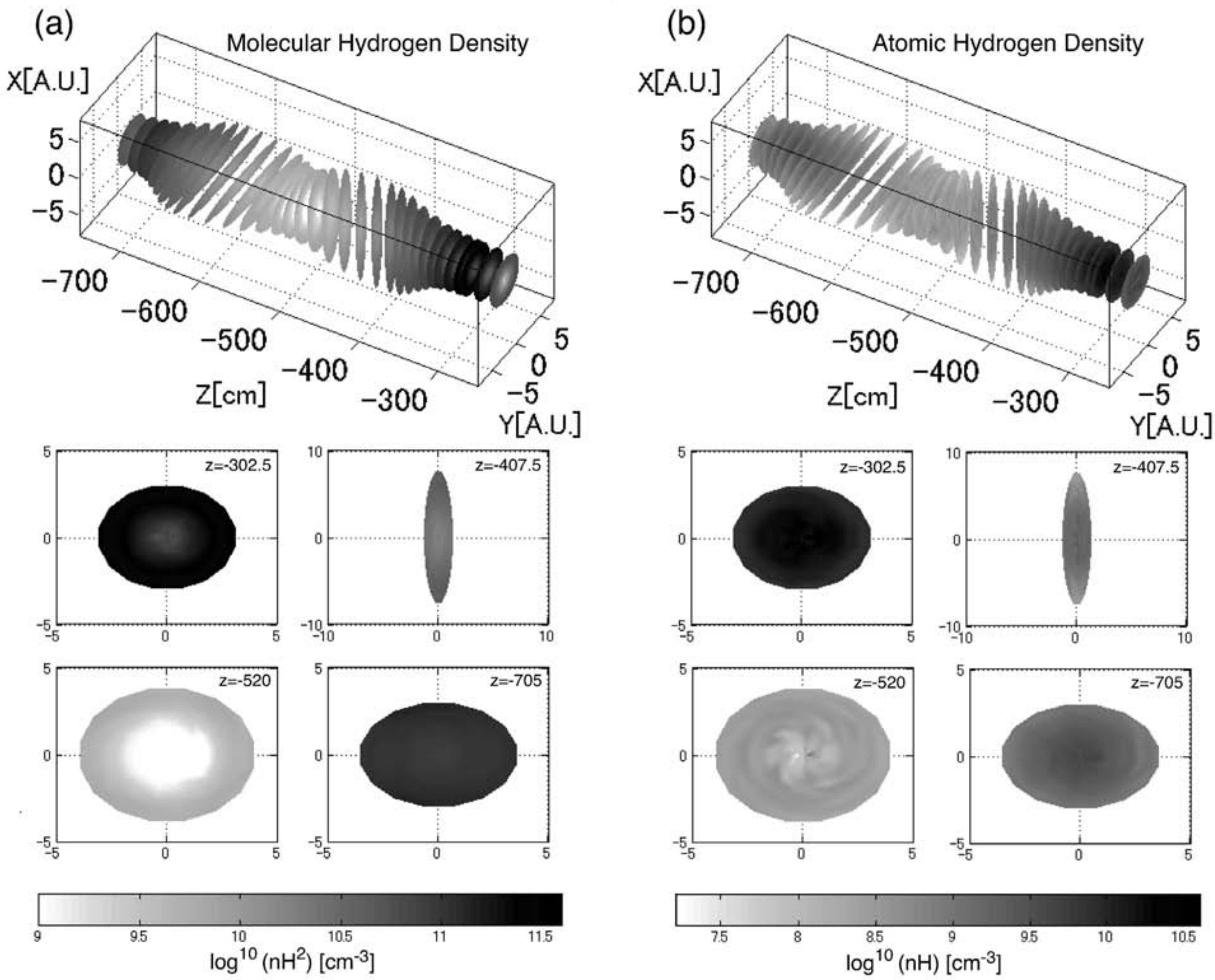

Fig. 3 Results of the 3D-DEGAS simulation in the case that the gas puffing at the mirror throat and gas desorption from the movable limiter in the outer-transition region is applied as the particles source. (a) molecular hydrogen, (b) atomic hydrogen.

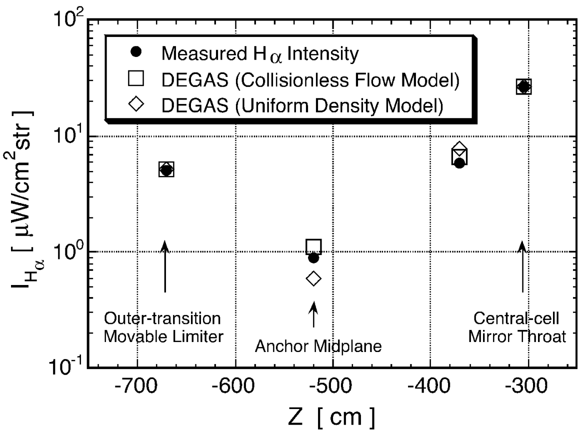

Fig. 4 Axial intensity profile of Hα line-emission.

results and measured one. Calculated results of Hα intensity obtained with two typical density models are normalized so as to fit to the measured results at each source location. The simulation assuming both particle sources from the gas puffer and from the movable limiter successfully reproduces the axial profile of measured Hα intensity. While, a small discrepancy is observed at the anchor midplane in the case of the uniform density model. The hydrogen recycling near the movable limiter plays an important roll on the behavior of neutral particles in the non-axisymmetric anchor region.

By accumulating the information of neutral density obtained above and the data of plasma parameters, total particle source rate from the central-cell to the anchor-cell is evaluated. An example of the results is shown in Fig. 5. In the figure, axial profiles of the particle source rate radially integrated up to r_{cc} = 20 cm are plotted in cases of given two density models. Here, r_{cc} represents the plasma radius reduced to that at the central-cell midplane along the line of magnetic force. There is no significant difference observed between both cases. The dissociative-excitation reactions of hydrogen molecules are presumably less effective on the Hα intensity than the dependence of the plasma density profile. As shown in the figure, it is found that the particle source rate in the mirror throat is dominant compared with those in the regions of the anchor midplane and of the movable limiter.

4. Summary

Using three-dimensional Monte-Carlo code DEGAS

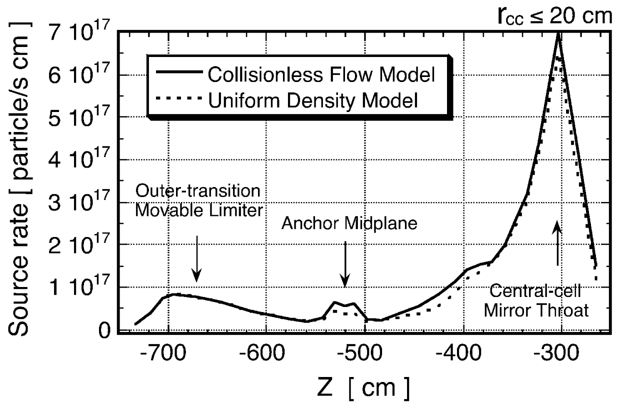

Fig. 5 Calculated axial profiles of the particle source rate integrated within r_{cc} = 20 cm.

ver.63, a modeling of neutral transport was successfully performed in the GAMMA 10 anchor-cell with non-axisymmetric configuration of the magnetic field, and the behavior of neutrals in this region was investigated on the basis of the experimental data of Hα line-emission measurements. From the simulation results, it was found that both particle sources from gas puffing at the central mirror-throat region and the hydrogen recycling from the movable limiter located in the outer-transition region predict the experimental results well. The estimation of ionization rate based on the simulation shows that ionization in the mirror-throat region is dominant in the total particle source in GAMMA 10. Comparison between the two typical density models in the anchor region indicates that the total ionization amount is not affected strongly by this difference. Above these results give an important subject on the investigation of the particle source-rate in the non-axisymmetric regions.

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