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Behavior of neutral-hydrogen and particle confinement on GAMMA 10 tandem mirror plasmas

Y. Nakashima [a,*], M. Shoji [a], K. Yatsu [a], S. Kobayashi [a], K. Tsuchiya [b], N. Yamaguchi [c], M. Yoshikawa [a], T. Aota [a], T. Ishijima [a], M. Ichimura [a], M. Inutake [d], A. Mase [a], T. Tamano [a]

[a] *Plasma Research Center, University of Tsukuba, Tsukuba, Ibaraki 305, Japan*

[b] *Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka-machi, Ibaraki 311-01, Japan*

[c] *Toyota Technological Institute, Nagoya 468, Japan*

[d] *Department of Electrical Engineering, Tohoku University, Sendai 980-77, Japan*

Abstract

Behavior of neutral hydrogen in the central-cell of the GAMMA 10 tandem mirror is investigated by measuring spatial-profiles of H α line-emission and neutral transport simulation. H α-emission detectors are newly installed horizontally in the vacuum chamber and detailed profiles of the H α emission are measured. It is found that hydrogen atoms introduced from the gas puffer at the mirror throat are localized around the gas puffer in the steady state phase of ICRF-heated plasmas. The DEGAS neutral transport code is applied to calculate axial density profiles of atomic and molecular hydrogen. In the DEGAS code, the mesh model is modified to take into account variations along the magnetic-field line. The simulation result fairly agrees with the above experimental result. In a standard ICRF-heated plasma, an experiment with modulated gas-puffing is performed. Characteristics of particle confinement in the main plasma are discussed by using the experimental and the simulation results.

Keywords: GAMMA 10; Tandem mirror; Neutral transport and confinement; Monte Carlo simulation; H-alpha line emission

1. Introduction

Neutral-hydrogen behavior is an important subject in discussing recycling phenomena and particle confinement on magnetically confined plasmas. It is also important in clarifying the characteristics of neutral particles for obtaining high-β plasmas and to analyze the particle balance in the tandem mirror devices [1–4]. H α line-emission from main plasmas has been measured in the central-cell of the GAMMA 10 tandem mirror and the neutral density has been estimated from its radial profile [5]. The neutral transport code by Monte-Carlo technique also has been applied to the central-cell and the atomic and molecular hydrogen profiles have been investigated on ICRF-heated hot-ion-mode plasmas [6]. Recently H α-emission detectors were newly installed horizontally in the central-cell vacuum chamber, which enables measurement of both axial and radial profiles of H α emission. The neutral transport code was modified to calculate the axial density profile of atomic and molecular hydrogen densities. In this paper detailed behavior of neutral hydrogen is described in terms of H α line-emission measurements and neutral transport simulation. The characteristics of particle confinement are discussed on the basis of particle balance analysis.

* Corresponding author. Tel.: +81-298 53 6268; fax: +81-298 53 6202.

2. GAMMA 10 and the experimental setup

GAMMA 10 is a tandem mirror device which consists of an axisymmetric central-mirror cell, anchor-cells with minimum-B field, and plug/barrier cells with axisymmetric mirrors [7,8]. The length of the central-cell is 6 m and the diameter of the vacuum chamber is 1 m. The magnetic strength in the central-cell mid-plane is normally 0.43 T

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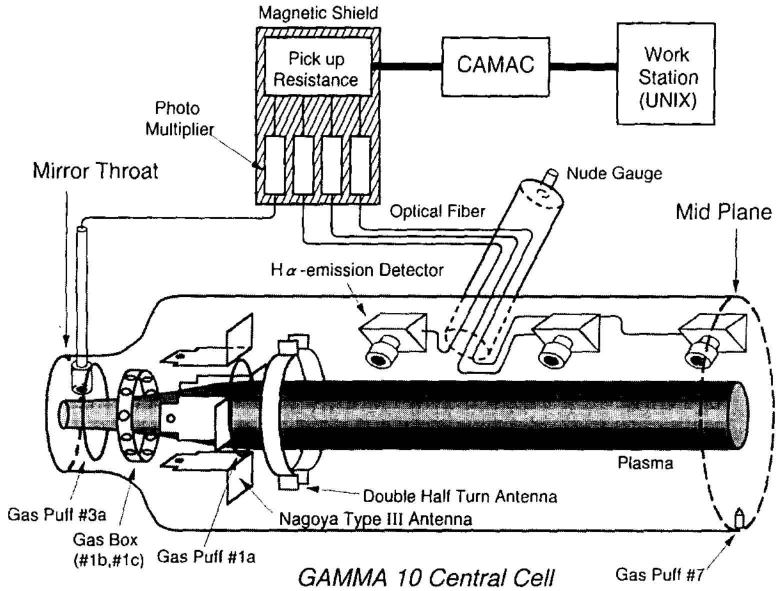

Fig. 1. Schematic view of one half of the GAMMA 10 central-cell and the ICRF antenna, the gas puffing system and the H α diagnostic system.

and varied from 0.3 T to 0.57 T. Both ends of the central-cell are connected to the anchor-cells via the mirror-throat regions. Initial plasma is injected from both ends by plasma guns, then a plasma is built up with ICRF wave together with gas puffing. The ion-confining potential and the thermal barrier potential at each end are formed by ECRH using gyrotrons.

Fig. 1 shows the schematic view of one half of the GAMMA 10 central-cell vacuum vessel and the plasma heating system, the gas puffing system and the diagnostic system for H α line-emission. Central-cell ions are heated by ICRF wave excited by a pair of the double half-turn antennas located near the ends of the central-cell. Seven gas puffers are installed in the central-cell and most of them are located away from the resonance layer in order to avoid the charge-exchange loss of hot ions. One of the newly installed H α-emission detectors is located on the mid-plane of the central-cell ($z = -1$ cm) and the other three detectors are installed at -71 cm, -141 cm and -307 cm away from the mid-plane, respectively. The detector located at $z = -307$ cm observes the H α emission at the mirror-throat region. Each detector consists of an H α filter, an optical fiber and a photomultiplier. The detected signal of H α line-emission is transferred to a CAMAC system and finally analyzed with a workstation. The detectors are absolutely calibrated with a standard lamp.

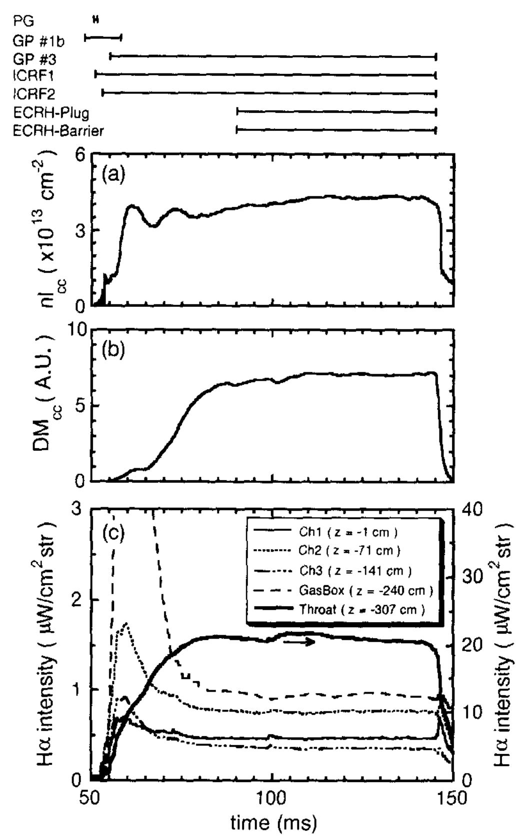

Fig. 2. Temporal behavior of plasma parameters in typical ICRF-heated plasmas. Central-cell electron line-density (a), diamagnetism at the central mid plane (b) and H α intensity measured at various axial positions from the mid-plane to the mirror throat (c).

3. Experimental results

In Fig. 2, a typical time behavior of plasma parameters and of H α line-emission is shown in the ICRF-heated

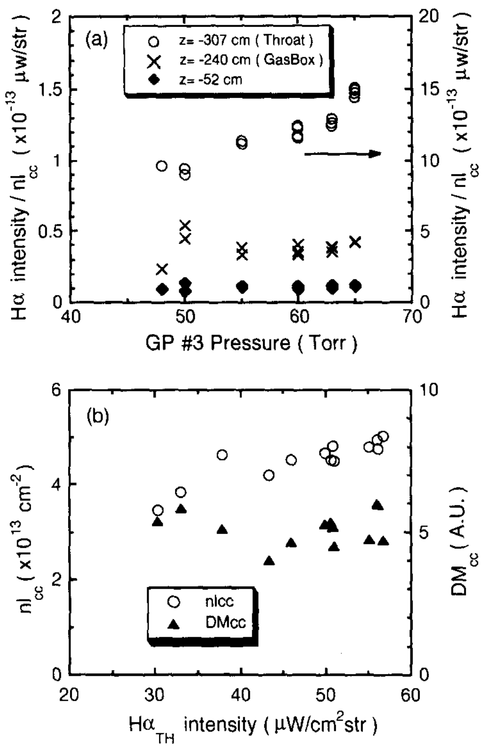

Fig. 3. Dependence of normalized H α intensity on the reservoir pressure of the gas puffer (a) and dependence of the electron line-density on the H α intensity measured at the mirror throat (b).

plasma. In this experiment, two types of gas puffers are used. One (GP#1b) is used for start-up of the plasma by injecting dense gas into the gas box with a short pulse. The other (GP#3a) is used for sustaining the plasma along with the ICRF pulse by continuously introducing gas in the mirror throat region. After turning-on the ECRH pulses, the electron temperature of 60–100 eV is obtained from soft X-ray measurements. Fig. 2c shows the intensity of H α emission measured with axially aligned detectors and those measured at the gas box and the mirror throat. At the initial phase of plasma start-up, the signal at the gas box has a strong peak. This indicates that the influence of the gas puffer GP#1b is dominant in the initial phase of plasma start-up. In a steady state phase, on the other hand, the H α intensity from the mirror throat is stronger than the other region, which implies that hydrogen atoms induced from GP#3a are localized around the mirror throat. The intensity of H α emission detected at the mirror throat is more than 20 times higher than that near the mid-plane.

Fig. 3 shows the dependence of H α intensity normalized by the electron line-density on the quantity of gas puffing into the mirror throat. The normalized H α intensity at the mirror throat is observed to increase with the reservoir pressure of the gas puffer. The intensities at the other positions, however, are insensitive to the quantity of gas puffing as shown in Fig. 3a. The electron line-density and the diamagnetism measured at the mid-plane are plotted in Fig. 3b as a function of the H α intensity at the mirror throat. Note that the line-density has a clear correlation with the H α intensity of the mirror throat and that the diamagnetism is less affected by the gas puffing. On the other hand, in the case where gas puffing is carried out directly into the mid-plane, it has been found that strong charge-exchange loss causes a considerable decrease of the diamagnetism without increasing the plasma density. Therefore gas puffing into the mirror throat region was confirmed to be effective to build up the central plasma density of mirror plasmas.

4. Neutral-transport simulation

In order to explain the experimental results, the DEGAS neutral-transport simulation code [9] was applied to estimate the axial profile of the atomic and molecular

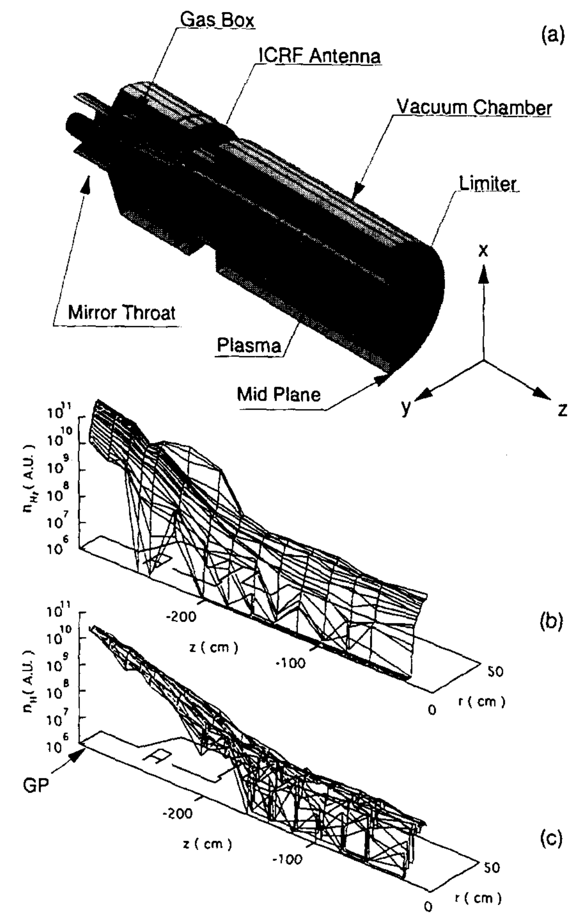

Fig. 4. Mesh model of the GAMMA 10 central-cell used in the DEGAS neutral transport code (a). 3-dimensional profiles of hydrogen density obtained by DEGAS; molecular hydrogen density (b) and atomic hydrogen density (c).

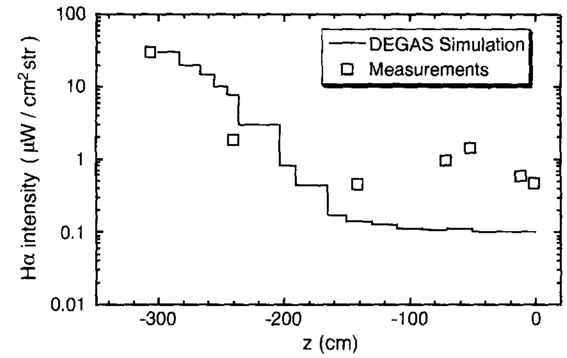

Fig. 5. Axial profile of H α intensity. Solid line represents the DEGAS simulation and the squares represent experimental results.

hydrogen density. In the DEGAS code, the effect on dissociative-excitation reactions of molecular hydrogen has been taken into consideration [6]. The code is also modified to take into account the variation along the magnetic-field line. Fig. 4 shows a new mesh model and the simulation results obtained under almost the same condition of the present experiment. The mesh model on one half of the central-cell is designed by assuming a axisymmetry of the vacuum chamber and ICRF antennas. In this simulation, hydrogen gas is injected into the mirror throat region. The axial and radial profiles of the electron density are estimated from the microwave interferometers located at both the mid-plane and the mirror throat, taking the shape of the magnetic flux into consideration. The axial profile of the electron temperature is given to be flat based on the measured data. As shown in Fig. 4c, atomic hydrogen density n_H decreases along the axial direction from the mirror throat to the central-cell mid-plane by more than 2 order of magnitude. The profile of n_H becomes flat in the vicinity of the mid-plane. These phenomena are thought to be ascribed to the barrier of gas transport due to the equipments installed near the end of the vacuum chamber, such as two ICRF antennas and the gas box. Fig. 5 shows the comparison between the simulation result and the measured H α intensity. The simulation result is fitted to the measured data near the mirror throat region ($z \approx -300$ cm). The simulation results fairly agree with the measured results. However, the measured data are higher than the simulation near the mid-plane ($0 \geq z \geq -150$ cm). This discrepancy may be ascribed to the strong hydrogen recycling due to the high energy charge-exchanged neutral particles [6,10].

5. Analysis of particle confinement

In a standard ICRF-heated plasma, an experiment with modulated gas puffing was performed and the resultant temporal-changes of the electron density and the H α emission were measured to evaluate the characteristics of particle confinement. In a nearly steady-state condition, a small amount of hydrogen gas is injected into the plasma from the gas boxes located near the mirror throat region (GP#1c). Fig. 6 shows the time evolution of the plasma parameters obtained in the modulated gas puffing experiment. Due to the slow response of the gas puffer installed in the gas box, there is a considerable delay (~ 20 ms) in the time behavior of the intensity of H α emission and the electron line-density in the central-cell. The H α intensity close to the gas box increases twice as much as without gas puffing. The line-density is also observed to increase by 20% due to the gas puffing. On the other hand, the mid-plane H α detector shows less increase during the gas puffing. This result supports that the ionization in the mirror throat region dominates fueling in the whole central region.

From these experimental results the characteristics of particle confinement can be obtained if the quality of particle confinement does not change before and after the modulation of gas puffing. The particle confinement time is determined from particle balance analysis with perturbation method by using the density change Δn_{CC} and the change of ionization of i-th segment in the axial direction ΔS_i associated with gas puffing as follows:

$$\tau_P = \frac{V_{CC} \Delta n_{CC} + V_{TH} \Delta n_{TH}}{\Sigma_i \{ \Delta S_i V_i \}}, \tag{1}$$

where V_{CC} and V_{TH} are plasma volume of central-cell and mirror throat region, respectively. The density change in the mirror throat region Δn_{TH} is obtained on the basis of the correlation between the line density in the central-cell and that in the throat region. The change of the ionization

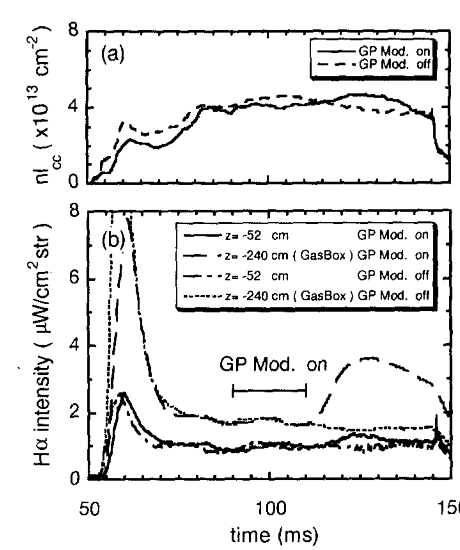

Fig. 6. Time evolution of plasma parameters obtained in the modulated gas puffing experiment; electron line-density (a), H α intensities measured at the gas box and near the mid-plane (b).

ΔS near the gas box is determined from the increase of $H\alpha$ intensity measured at the gas box. The axial variation ΔS_i can be determined by fitting the result of the DEGAS simulation, in which the gas is introduced from the gas box, to the measured intensity at the gas box. By using the above method the particle confinement time is estimated to be 7-10 ms in the present experiment. This value is comparable with the energy confinement time in typical hot-ion-mode plasmas [8], which shows that the modulated gas-puffing experiment adequately evaluates the particle confinement in the tandem mirror plasma.

6. Summary

$H\alpha$-emission detectors were newly installed horizontally in the central-cell of the GAMMA 10 tandem mirror and axial profiles of the $H\alpha$ emission were measured for the first time in ICRF-heated plasmas. It was found that hydrogen atoms introduced from the gas puffer at the mirror throat were localized around the gas puffer in the steady state plasmas. This result fairly agrees with the results of the neutral transport simulation by the DEGAS code. It was observed that there is a strong correlation among the intensity of $H\alpha$ emission, electron line-density in the central mid-plane and the quantity of gas puffing at the mirror throat. The modulated gas puffing experiment was carried out and the resultant particle confinement time was consistent with the energy confinement property in the typical hot-ion-mode plasma.

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References

[1] W.L. Pickles, M.O. Calderon, M.R. Carter et al., J. Vac. Sci. Technol. A 1 (1983) 1288.
[2] R.A. Breun, D.A. Brouchous, J.R. Conrad et al., J. Vac. Sci. Technol. A 5 (1987) 265.
[3] R.S. Post, K. Brau et al., J. Nucl. Mater. 145-147 (1987) 81.
[4] Y. Nakashima, N. Yamaguchi, K. Yatsu et al., J. Nucl. Mater. 220-222 (1995) 580.
[5] N. Yamaguchi, S. Adachi, T. Cho et al., Proc. 15th Eur. Conf. on Controlled Fusion and Plasma Heating, Dubrovnik, Vol. 12B (1988) part II, p. 593.
[6] Y. Nakashima, K. Yatsu, K. Tsuchiya et al., J. Nucl. Mater. 196-198 (1992) 493.
[7] T. Tamano, T. Cho, M. Hirata et al., Proc. 15th Int. Conf. on Plasma Phys. and Controlled Nucl. Fusion Research, Seville, 1994, Vol. 2 (IAEA, Vienna, 1995) p. 399.
[8] T. Tamano, Phys. Plasmas 2 (1995) 2321.
[9] D. Heifetz, D. Post, M. Petravic et al., J. Comput. Phys. 46 (1982) 309.
[10] Y. Nakashima, K. Yatsu, K. Tsuchiya et al., J. Nucl. Mater. 200 (1993) 351.