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Hydrogen Recycling in a Long-Pulse Discharge Plasma on the Tandem Mirror GAMMA 10

KOBAYASHI Shinji*, NAKASHIMA Yousuke, SHOJI Mamoru[1], TSUCHIYA Katsuhiko[2], ISHIMOTO Yuki,
AMINAKA Hiroaki, YAMAGUCHI Naohiro[3], YOSHIKAWA Masashi, TAMANO Teruo and YATSU Kiyoshi
Plasma Research Center University of Tsukuba, Tsukuba 305-8577, JAPAN
[1]National Institute for Fusion Science, Toki 509-5292, JAPAN
[2]Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka-machi 311-0102, JAPAN
[3]Toyota Technological Institute, Tempaku-ku, Nagoya 468-8511, JAPAN

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Abstract

A gas dynamic pressure calculation was modified in order to investigate hydrogen recycling under quasi-steady state condition in the long-pulse discharge plasma of GAMMA 10. We estimated the temporal behavior of the fueling rate of the recycling from wall surface by a gas dynamic pressure analysis. It is found that the hydrogen recycling enhances with the ion temperature in the GAMMA 10 central cell. The quantity of the wall recycling was also estimated by using DEGAS neutral particle transport simulation. The wall recycling deduced from DEGAS fairly agree with that by the dynamic pressure analysis.

Keywords:
hydrogen recycling, gas dynamics, neutral particle transport simulation

1. Introduction

Quantitative analysis of fueling from beam injection, gas puffing and recycling, is an important issue for particle confinement and steady state operation in fusion devices. In the GAMMA 10 device [1], the long-pulse discharge experiment (~0.5 s) was attained by ion cyclotron range of frequency (ICRF) heating [2]. The duration of potential confinement had been extended from 0.075 s to 0.15 s by using two microwave heating (ECRH) systems [2]. The pulse duration of ICRF and ECRH systems are limited by each power supply. Dominant processes in plasma-wall interaction (PWI) in the GAMMA 10 plasma is bombardment of charge exchange (CX) neutrals onto the wall surface, because the plasma density is relatively low (~2×10^{18} m^{-3}) and the ion temperature is high (several keV). In the particle balance between fueling and loss in a mirror plasma, plasma-pumping effect is important and it is an essential characteristic in open-end system [3,4]. Under these situations, it is an interesting problem to find the way to steady-state operation from the view point of the plasma-wall interaction.

The hydrogen recycling in GAMMA 10 has been analyzed by a gas dynamic pressure calculation based on pressure-balance equation including the plasma-pumping effect [5]. The dynamic pressure calculation had been applied to plasma duration which is shorter than 0.1 s, then, we modified the calculation for the long-pulse discharge experiment. In the calculation, the GAMMA 10 central cell had been treated as one volume section, that is, the gas pressure in the central cell had been assumed uniform. In the present experimental

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*Corresponding author's e-mail: shinji@prc.tsukuba.ac.jp configuration in GAMMA 10, however, the pressure gradient along the magnetic field has been confirmed by the H_α emission measurement and neutral transport simulation with DEGAS code [5-7]. Therefore, we modified the dynamic pressure calculation by dividing the central cell into four regions.

The aim of this study is to investigate a transition of recycling in the long-pulse discharge experiment. The scope of the work contains the recycling study in the longer duration of potential confinement in the future experiment. In this paper, we estimate the fueling rate of wall recycling by the gas dynamic pressure calculation. We established the estimation method for the quantity of the wall recycling by using the DEGAS code. The quantity of the wall recycling by DEGAS is compared with that from the dynamic pressure calculation.

2. Analysis Method

Figure 1 illustrates the schematic diagram of one half of the GAMMA 10 volume-conductance model used for the gas dynamic pressure calculation. GAMMA 10 consists of several vacuum chambers, such as a central cell, anchor cells, plug/barrier regions, end cells, neutral beam injector (NBI) tanks and beam dumps. Several ducts with relatively small conductance link these chambers to each other. For maintaining the plasma, hydrogen gas was continuously supplied from the gas puffer located at the end of the central cell ($GP_{\#3}$). This method has effectively prevented CX loss of hot ions in the central cell. The central cell ions were heated by ICRF wave (RF2). For plasma production and/or ion heating in anchor cell, we used another ICRF system which is called RF1.

In open-end systems, fueled particles in the central cell are almost lost to the end by the plasma pumping. Gas pressure in the i-th chamber can be described as following pressure-balance equations,

$$V_i \frac{dP_i}{dt} = Q_{GP} + \Delta Q_{WR} - S_i P_i + \sum C_{ij} \left(P_j - P_i\right) - Q_{PP} \qquad (1)$$

where, P and V are pressure and volume, respectively. The third term of the right side is pumping with speed S. C_{ij} is a conductance between the i-th and the j-th chamber. Q_{GP} is a gas flow rate from the gas puffer. Q_{PP} represents the plasma pumping which is taken as the particle source calculated from H_α emission measurement. From the equations, the fueling rate of the hydrogen recycling from the wall ΔQ_{WR} is finally determined so as to reproduce the dynamic pressure during a plasma discharge measured by several nude-gauges.

In order to analyze the localized hydrogen recycling induced by the high energy CX neutrals originated from the hot ions trapped around the central cell midplane, we divided the central cell vacuum vessel into four regions. This modification enables us to estimate localized ΔQ_{WR} around the midplane. We also modified it so as to separate the wall fueling from the gas puffing at both ends of the central cell.

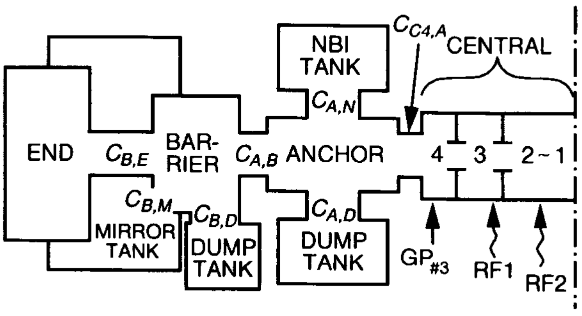

Fig. 1 The schematic view of the one half of the GAMMA 10 vacuum vessel for the gas dynamic pressure calculation.

3. Results

Figure 2 shows the temporal behavior of plasma parameters in the long-pulse discharge experiment for recycling studies. In this experiment, the confining potentials were not formed so that we can observe clearly the plasma pumping effect directly from the pressure measurement. To examine the dependence on the ion temperature, the RF2 power (P_{RF2}) was varied from 32 kW to 96 kW, while other parameters (the RF1 power or gas puffing) were not changed. The diamagnetism at the central cell midplane (DM_{CC}) shown in Fig. 2(a) increases by five times with increasing P_{RF2} from 32 kW to 96 kW. The averaged ion temperature increases from 0.3 keV to 1.3 keV. Temporal behaviors of the measured gas pressure in the central cell and end cell are shown in Fig. 2(b) and (c) by solid and dotted lines. Each gas pressure gradually reaches a stationary condition in the latter half of the discharge. The gas pressure without plasma in the central cell was about ten times higher than that with the plasma discharge. In the end cell, on the other hand, the pressure rise in the no plasma case was not observed because of the small conductance between the two regions. The reduced pressure in the central cell and increased end cell pressure caused solely by the effect of the plasma pumping. The rise of the end cell pressure

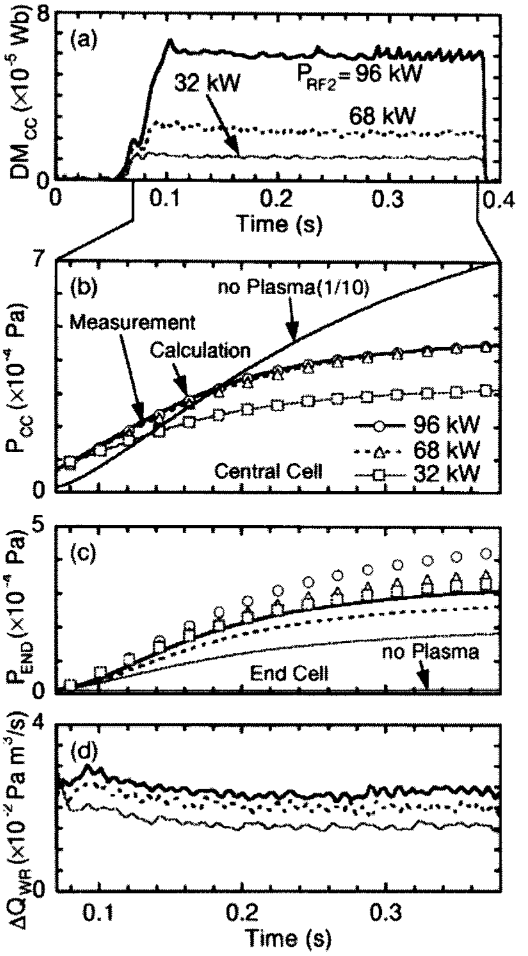

Fig. 2 Time evolution of the long-pulse discharge experiment, (a) diamagnetism at the central cell midplane, (b) hydrogen gas pressure in the central cell and (c) end cell, (d) flow rate of the wall recycling. Open symbols shown in 2(b) and (c) are the results of gas dynamic pressure calculation.

was enhanced with the central cell ion temperature, which was, then, due to increase of the quantity of plasma pumping.

Open symbols in Fig. 2(b) and (c) show time evolutions of the calculation results for the gas dynamic pressure analysis under three cases of the RF2 power 32 kW, 68 kW and 96 kW. The dynamic pressure was analyzed in one half of the GAMMA 10 device. As shown in Fig. 2(b), the calculated pressure in the central cell almost reproduces the measured one. The end cell pressure from the calculation, on the other hand, is about 40% higher than that from the measurement. This discrepancy may be caused by measurement error or uncertainty of the volume-conductance model, however

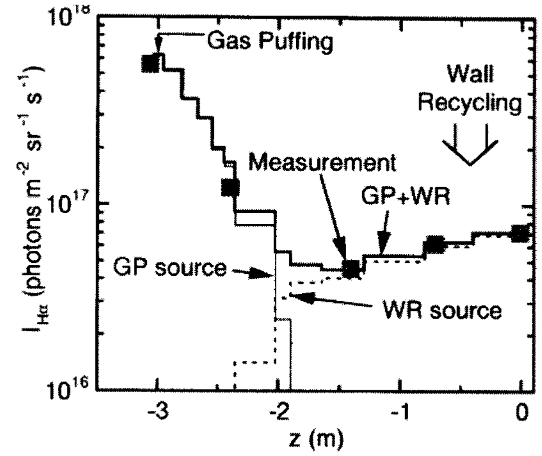

Fig. 3 An example of the axial profile of the H-alpha intensity in the central cell deduced from the DEGAS simulation (lines). Square symbols show the measured intensity.

the dependence on the RF2 power increase is consistent with the measured result. The quantity of wall recycling ΔQ_{WR} near the central cell midplane is shown in Fig. 2(d). It was found that the ΔQ_{WR} slightly decreased in the period from 0.1 s to 0.2 s and reached almost quasi-steady state condition in the following period. Note that the ΔQ_{WR} increases with increasing P_{RF2}. This indicates that the hydrogen recycling near the central cell midplane is enhanced by the increase of the ion temperature.

4. Discussion

For the detail quantitative analysis on the hydrogen recycling, we estimated the quantity of wall recycling by using the DEGAS code. For neutral particle transport analysis in the GAMMA 10 plasma, we have used a combination of H_α emission measurement and DEGAS particle transport simulation [5-7]. This code has been modified to take into account the dissociative-excitation reactions of neutral hydrogen molecules in order to apply to the low plasma density in GAMMA 10 [5].

Figure 3 shows an example of the simulation at 0.25 s in the discharge with the RF2 power of 68 kW. In this simulation, we considered two types of gas sources. One is gas puffing (GP) source located at both ends of central cell ($GP_{\#3}$). Another is the recycling source from the wall surface (WR) around the central cell midplane. Test particles launched from the gas puffer and the wall surface were treated as the number of hydrogen molecules with the wall temperature per unit time. Each fueling rate was, then, determined so as to reproduce the

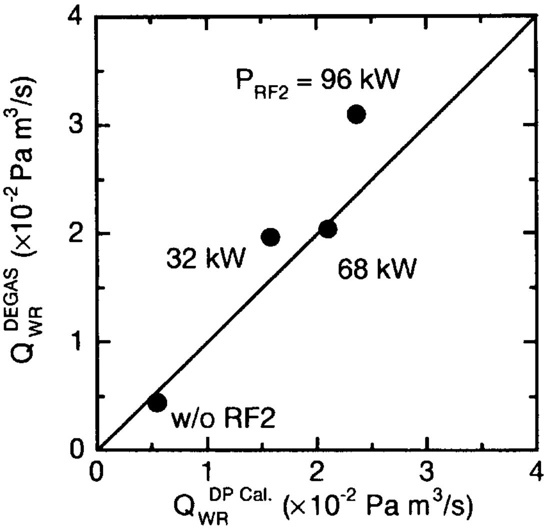

Fig. 4 Comparison between the quantity of wall recycling from the gas dynamic pressure analysis and that deduced from the DEGAS simulation.

measured H_α intensity. The flow rate from the gas puffing was set to be about 8×10^{-2} Pa m^3/s, while the quantity of wall recycling was 2×10^{-2} Pa m^3/s. It is expected that the plasma is maintained in a quasi-steady state by the fueling from the gas puffing and the recycling.

Figure 4 shows the comparison of the analysis results on hydrogen recycling by using two methods. $\Delta Q_{WR}^{DP\ Cal.}$ is the quantity of wall recycling deduced from the gas dynamic pressure calculation, and ΔQ_{WR}^{DEGAS} from the DEGAS code. We carried out the simulation in three cases of the RF2 power and no RF2 heating. These data fairly agree with each other, which indicates consistency of two estimation methods for the quantity of wall recycling.

5. Conclusion

We modified the gas dynamic pressure calculation for the long-pulse discharge experiment. We observed the temporal behavior of the quantity of hydrogen recycling around the central cell midplane under quasi-steady state condition. It was found that the quantity of the recycling near the midplane enhanced with the ion temperature in the central cell. The quantity of the wall recycling was also estimated by use of the combination of the DEGAS simulation and the H_α emission measurement. In the discharge with the RF2 power of 68 kW, the fueling rate of the gas puffing and wall recycling was evaluated to be about 8×10^{-2} Pa m^3/s and 2×10^{-2} Pa m^3/s, respectively. In this experimental condition, it is expected that the plasma is maintained in a quasi-steady state by the fueling from the two sources. We confirmed that the wall recycling deduced from the simulation agreed with the result from the gas dynamic pressure calculation.

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