ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 297–301

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Behavior of helium gas in the LHD vacuum chamber

H. Suzuki *, N. Ohyabu, A. Komori, T. Morisaki, S. Masuzaki, J. Miyazawa, R. Sakamoto, M. Shoji, M. Goto, S. Morita, Y. Kubota, O. Motojima, The LHD Experimental Group

National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan

Abstract

In general, helium gas does not remain on vacuum chamber walls because of its small activation energy. However, outgassing of helium gas from the walls has been observed in the LHD plasma vacuum chamber with a very long time constant after helium glow discharge cleaning (GDC), and absorption of helium atoms has been observed in plasma discharge experiments using helium gas. The helium partial pressure before the daily experiments was determined only by the gas species of the last GDC. No dependence has been found between the helium partial pressure and the species of the fueling gas of the last plasma experiment fueling gas. Considering that the outgassing rate of the helium gas is almost the same each morning after He GDC, the retention of helium atoms in the wall after the GDC is almost at the same level. The concentration of helium atoms in the wall before the daily experiments is estimated. The outgassing rate after the GDC is 2×10^{-4} Pa m^3/s and the concentration is 4.7×10^{16} atoms/cm^2. These results are of the same order as in another experiments. During helium gas plasma experiments, about a half of the amount of the inlet gas disappears with the missing particles remaining in the wall. The stainless steel wall, which is saturated with He GDC, may still have the capacity to trap high energy helium atoms. However, the energy dependence of trapping helium atoms presently is not clear.

PACS: 52.40.Hf
Keywords: LHD; Helium retention; Outgassing; Stainless steel; Wall conditioning; Implantation

1. Introduction

It is well known that helium atoms are not retained in metal walls to the extent that hydrogen atoms are. Helium gas is easily released from the surface of the wall because of its small desorption activation energy of 590 J mol^{-1}. Therefore, in general, helium gas is not significantly trapped in vacuum vessels [1]. However, in the case of plasma discharges, the behavior of helium atoms in the wall could be different. Trapping of helium gas in materials after beam injection experiments or glow discharges has been reported in a few devices [2–4]. In the case of the TJ-II stellarator, the absorption of helium gas during glow discharge cleaning (GDC) and the desorption of helium gas during the main plasma experiments have both been observed. Due to the helium gas desorption during the main plasma discharge, TJ-II had difficulty in controlling the plasma density [2]. Such a density control problem does not exist in the LHD experiment. However, trapping of helium atoms is also observed in the LHD case, and desorption of the helium gas in LHD makes the ICRF heating condition unsteady, and makes helium leak testing difficult.

Main plasma discharge experiments in the LHD have been carried out using hydrogen and helium gas. During a typical experiment day, the plasma is produced every 3 min. The discharge time of each shot is typically a few seconds. After the main plasma discharge experiments,

* Corresponding author. Tel.: +81-527 58 2148; fax: +81-527 58 2618.
E-mail address: hsuzuki@lhd.nifs.ac.jp (H. Suzuki).

0022-3115/03/$ - see front matter
PII: S0022-3115(02)01584-2

He GDC or H_2 GDC is applied. The details are described in Section 2.

During the hydrogen plasma experiment, helium gas has been observed not only by the mass spectrometer but also by the optical spectrometer. The behavior of the helium during the main experimental discharges is analyzed and discussed.

2. Apparatus

The vacuum vessel of LHD with a volume of 210 m^3 and a total surface area of 730 m^2 is pumped out by four turbo molecular pumps (TMPs) and ten cryo pumps [5]. The cryo pumps have charcoal walls, which can capture helium atoms. The maximum pumping speed has been estimated to be 141 m^3/s (hydrogen gas) and 62 m^3/s (helium gas) by analyzing curves of pressure decay. The pumping speed during helium GDC is reduced to 2 m^3/s (helium gas). After the GDC, the vessel is pumped out by only TMPs with a pumping speed of 17 m^3/s (helium gas). The vacuum vessel consists of stainless steel (SUS316L) with a total area of 700 m^2 including ports and graphite armor tiles with a total area of 30 m^2. The temperature of the wall is kept at about 25 °C by a water cooling system. Baking of the vessel is carried out during the weekend. However, the baking temperature is limited to less than 95 °C for protection of the superconducting magnets.

LHD has a quadruple mass spectrometer (QMS). By differential pumping, partial pressures in LHD can be measured under high pressure condition such as He GDC. The partial pressures are recorded every 15 s. The sensitivity of the QMS is calibrated by referring to the total pressure in the LHD vacuum chamber with helium or hydrogen gas.

Neutral gas pressure in the LHD vacuum vessel during the main plasma discharge experiments is measured by a fast ionization gauge (FIG), which is operational at high magnetic fields [6]. By combining the data of a gas puffing system with that of pumping system on the LHD, the particle balance in the vacuum vessel can be calculated. For precise measurement, the ionization factor of the measured gas is carefully applied.

After the main plasma experiments, a He GDC or a H_2 GDC is carried out for about 8 h at night. Then the GDC is terminated, and the vacuum vessel is pumped out. However after 7 h of pumping, the main gas in the vacuum vessel is helium after a He GDC. During the weekend, a long duration GDC is carried out with 95 °C baking. The GDC system of the LHD has two power supplies and two electrodes. The pressure during the GDC is about 1 Pa. The voltage and electric current are 200 V and 22 A, respectively, in the case of He GDC. The voltage and an electric current are 300 V and 22 A, respectively, in the case of H_2 GDC.

3. Experimental measurement and analysis

3.1. Outgassing of helium gas before the daily experiments

Fig. 1 shows the partial pressures of the helium gas at the starting time of the main plasma discharge experiment, which is about 7 h after the end of GDC. It is clear that the partial pressure of the helium gas is low after the H_2 GDC. After He GDC, the helium pressure has been at almost the same level every morning. No correlation is found between the helium pressure and the gas species of the last main plasma experiment. The helium pressure before the daily experiment has been determined only by the last GDC.

Fig. 2 shows the average of helium partial pressure at the same time as Fig. 1 after He GDCs as a function of discharge time. The error bar of the pressure shows the standard error. The error bar of the time shows the range of data used for making the plot point. After a total of 4 h of discharge, a significant relationship has not been observed between the helium partial pressures before the daily experiment and the duration time of GDC, considering the error. The wall may be saturated by helium gas after more than 4 h of He GDC. The total outgassing rate is estimated to be about 2×10^{-4} Pa m^3/s at a pumping speed of 17 m^3/s.

3.2. Absorption of the helium atoms during helium plasma experiments

During the main plasma discharge experiments, a net loss of helium particles is observed. Fig. 3(a) shows a comparison between the calculated total amount of helium atoms in the vacuum vessel using gas input flow data and evacuated gas data, with the total amount of

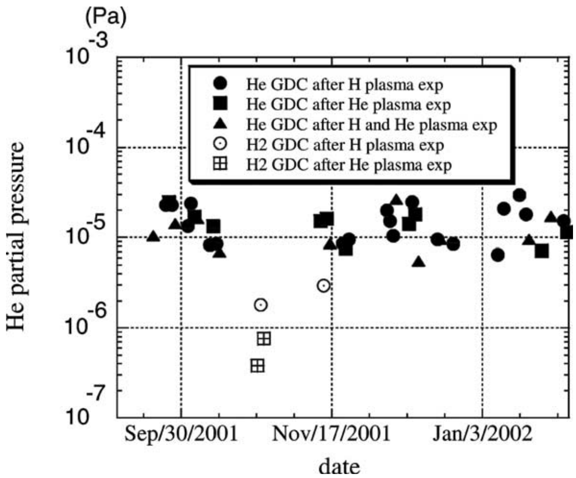

Fig. 1. Partial pressures of helium gas before the daily experiment after several main plasma experiments and GDCs.

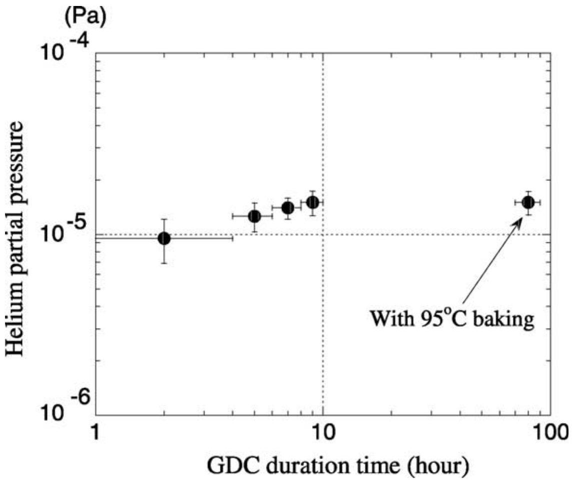

Fig. 2. Average partial pressures of helium gas before the daily experiment as a function of GDC duration. The error bar of pressure shows the standard error. The error bar of time shows the range of data used for making the plot point.

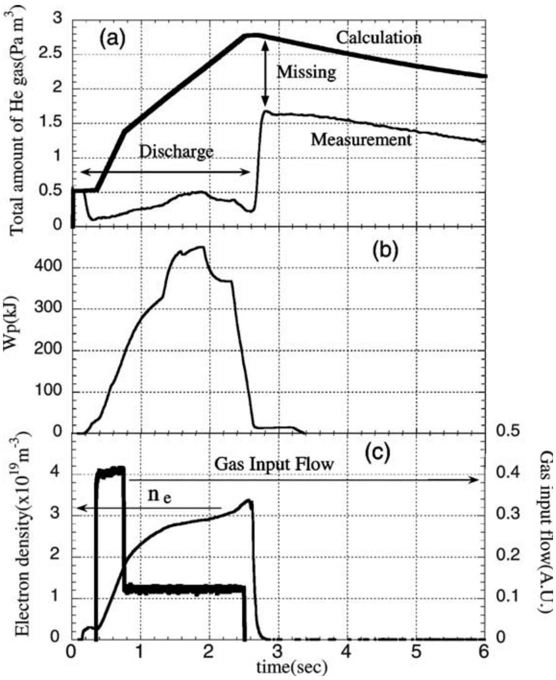

Fig. 3. (a) Total amount of helium atoms in the LHD vessel calculated using gas input flow data and evacuated gas data, with the total amount of helium gas determined from FIG data. (b) Plasma stored energy. (c) Electron density and gas input flow.

helium atoms measured by the FIG. The formula of the calculated total amount of helium atoms is given in Appendix A. The difference between the calculated value and the measured value is the missing helium atoms, which were presumably implanted into the wall. Stored energy, electron density and gas input flow rate are also shown in Fig. 3(b) and (c).

Before the main plasma discharge experiment, a test of the gas puff valve is carried out without plasma heating. In the case of helium gas puffing without plasma, no missing helium is observed. This implies that loss of helium atoms is due to their implantation, not low energy surface absorption. During the first campaign of the LHD experiment, no loss of the helium gas was reported [7]. However the loss of helium gas has been observed when plasma stored energy has been increased. Although the wall had been saturated by helium atoms after He GDC, still the loss of the helium atoms has been observed during the plasma experiments.

Assuming no wall pumping, the pressure after a plasma discharge can be estimated by the total amount of inlet helium gas and pumped out gas. Fig. 4 shows the ratios of the measured gas pressure and the calculated gas pressure with no wall pumping assumption for each plasma shot as a function of the plasma stored energy. If the wall does not pump helium gas, this ratio is unity. In most of cases, the ratios are about 0.5, so almost half of the inlet helium gas is implanted into the wall. Is the implanted helium being released during the 3 min interval of the plasma shot? Analyzing the trend of the helium gas pressure in the LHD vacuum vessel during the helium – main plasma discharge experiment, particle balance at the end time of the plasma experiment is studied. In the case of the experiment (7th November 2000), the total amount of inlet helium gas is calculated to be 516.6 Pa m^3 by analyzing the voltage of the gas puff valve. The total amount of pumped out gas is also calculated to be 227.5 Pa m^3 by analyzing the helium gas pressure and pumping speed. So at the end of the plasma discharge experiment, a large fraction of helium is still missing. Therefore the helium atoms were not released during 3 min interval.

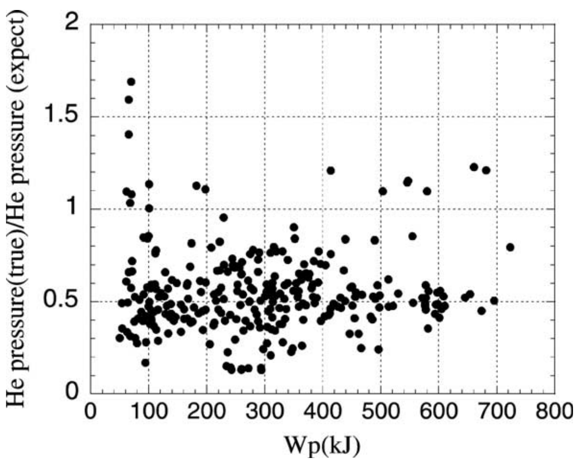

Fig. 4. Ratios of expected pressure with no wall pumping assumption and true pressure after a plasma shot.

Table 1
Operation status of the LHD, pressures, outgassing rate, and retention of helium atoms in the wall on 13th–14th November 2001

Time and date	Status	He partial pressure (Pa)	He outgassing rate ($Pa\,m^3/s$)	He retention in the wall ($Pa\,m^3$)
9:50, 13th November	Plasma experiment start (after He GDC)	1.5×10^{-5}	9.3×10^{-4}	Initial retention:Qinit (He GDC saturation level)
9:50–18:00	H plasma experiment	10^{-5}–10^{-3} (not steady)	–	(958 $Pa\,m^3$ of He was pumped out)
18:00	End of plasma experiment	4×10^{-4} (not steady)	–	Qinit – 958
21:00–3:00, 14th November	H_2 GDC	10^{-3}–10^{-4} (not steady)	–	(66.5 $Pa\,m^3$ of He was pumped out)
3:00	End of H_2 GDC	1×10^{-4} (not steady)	–	Qinit – 1024.5
3:00–9:50	Pumping	3–4×10^{-6} (not steady)	–	(0.1 $Pa\,m^3$ of He was pumped out)
9:50	Plasma experiment start	2.9×10^{-6}	1.8×10^{-4}	Qint – 1024.6

3.3. Estimation of helium in the wall

On 13th November 2001, a hydrogen plasma discharge experiment was carried out after He GDC. During the plasma discharge experiment, no helium gas was introduced into the vacuum chamber. However helium gas, which had been released from the wall by hydrogen atom bombardment was observed during the experiment. After the main plasma experiment, H_2 GDC was carried out. Helium gas from the wall was observed again. Using pressure data and pumping speed, the total amount of helium atoms removed can be estimated. Table 1 shows the status of the LHD operation of 13th–14th November 2001, the pressures at the time, helium outgassing rate, etc. The helium atoms in an amount of 958 $Pa\,m^3$ were removed during the main plasma experiment, and an amount of 66.5 $Pa\,m^3$ were removed during and after the H_2 GDC. Consequently the helium atoms with a total amount of 1024.6 $Pa\,m^3$ were removed by the hydrogen atom bombardment, and the helium partial pressure before the daily experiment reduced from 1.5×10^{-5} to 0.29×10^{-5} Pa.

In the initial stage, the amount of helium atoms in the wall is the He GDC saturation level (Qinit). The Qinit could not be measured directly, however, by assuming that the outgassing rate of helium gas is proportional to the number of the helium atoms in the wall, Qinit can be calculated. The Qinit has been estimated to be 1270 $Pa\,m^3$.

4. Discussions

From the viewpoint of solid state physics, helium atoms cannot be trapped in solution like hydrogen atoms. However, the helium atoms may be trapped in lattice defects. Candidates for trappings material in LHD are the stainless steel wall (SUS316L) with a total area of 700 m^2 and graphite tiles with a total area of 30 m^2. Kubota et al. reported a comparison of retention of helium gas in stainless steel and graphite tiles after helium glow discharge [8]. According to this reference, the capacity of the stainless steel per unit area is more than the capacity of the graphite tile of the same area. Considering these results, and the areas of stainless steel and graphite tiles, the main source of helium gas desorption in the LHD is the stainless steel wall.

An outgassing rate of helium gas from stainless steel walls (EN58B/AISI321) after a He GDC was reported by Govier and McCracken. Their result is 1.4×10^{-10} $Torr\,l\,s^{-1}\,cm^{-2}$ (1.9×10^{-11} $Pa\,m^3\,s^{-1}\,cm^{-2}$) [3]. If the source of helium gas with an outgassing rate of 2×10^{-4} $Pa\,m^3/s$ in LHD is the stainless steel wall, then the outgassing rate per unit area is 2.9×10^{-11} $Pa\,m^3\,s^{-1}\,cm^{-2}$ for LHD. This is in good agreement with Ref. [3].

Material probes of SUS316L have been installed in LHD. Hino et al. reported the gas desorption from the probe following 600 °C baking. According to this report the helium desorption amounts from the sample are not uniform, and the maximum released helium quantity is about 1×10^{16} atoms/cm^2 [9]. If helium atoms in the amount of 1270 $Pa\,m^3$ have been trapped in the stainless steel wall, the concentration is 4.7×10^{16} atoms/cm^2. This result is of the same order as the result of the material probe analysis.

In helium plasma experiments, about a half of the inlet helium is implanted into the wall, even though the wall is saturated with helium atoms by the He GDC. High energy helium atoms, which are produced by charge exchange interaction, have been implanted into the stainless steel wall, and trapped in lattice defects. Currently there is no estimation of the energy spectrum of the high energy helium flux. Considering the ion temperature profile of the helium plasma, the helium atoms with an energy of more than 300 eV are expected to exist at the edge of the LHD plasma. The stainless steel wall, which was saturated with helium atoms of 200 V produced by the He GDC, may still have a capacity for trapping high energy helium atoms. However, the energy dependence of the trapping of helium atoms is not well known now.

Considering that the outgassing rate of the helium gas every day after He GDC is almost at the same level before the daily experiment, the trapped helium atoms during the helium plasma experiment are removed by the He GDC and the concentration of the helium atoms in the wall returned the same level, which is estimated to be 1270 Pa m^3.

5. Conclusion

The behavior of helium gas in LHD has been studied. Each day after He GDC, the outgassing rates of the helium gas before the daily experiment have been at almost the same level. No correlation with the fueling gas of the last plasma experiments is found. With a few assumptions, the outgassing rate and concentration of helium in the wall following the He GDC are estimated. The outgassing rate after the GDC is 2×10^{-4} Pa m^3/s and the concentration is 4.7×10^{16} atoms/cm^2. These results are very similar to previous experimental results. The outgassing rate of the helium gas can be reduced by H_2 GDC.

Highly energetic helium atoms produced during the helium plasma experiments have been implanted into the wall. The implanted helium atoms remain in the wall until the end of the plasma experiment, and are removed by GDC.

Appendix A

Assuming no wall pumping effect, the total amount of He atoms in the vacuum chamber is given by

$$Q(t) = Q(0) + \int_0^t [q_{\mathrm{gas\_in}}(t) - P(t)s]\,\mathrm{d}t, \tag{A.1}$$

where $q_{\mathrm{gas\_in}}(t)$: gas input flow rate at time 't' (Pa m^3 s^{-1}), estimated by gas puffing valve voltage, $P(t)$: pressure (Pa), measured by the FIG, s: pumping speed (m^3 s^{-1}) (62 m^3/s), $Q(0)$: initial state, given by $P(0) \times V$ (Pa m^3), V: vacuum chamber volume (m^3) (210 m^3).

References

[1] G.F. Weston, Ultrahigh Vacuum Practice, Butterworths, London, 1985.
[2] D. Tefalla, F.L. Tabares, J. Nucl. Mater. 290–293 (2001) 1195.
[3] R.P. Govier, G.M. McCracken, J. Vac. Sci. Technol. 7 (1970) 552.
[4] S. Nagata, K. Takahiro, J. Nucl. Mater. 290–293 (2001) 135.
[5] M. Fujiwara et al., J. Fusion Energy 15 (1996) 7.
[6] G. Haas et al., J. Nucl. Mater. 121 (1984) 155.
[7] H. Suzuki et al., J. Plasma Fusion Res. Series 3 (2000) 250.
[8] Y. Kubota et al., these Proceedings. PII: S0022-3115(02)01486-1.
[9] T. Hino et al., J. Nucl. Mater. 290–293 (2001) 1176.