Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Nuclear Materials 337–339 (2005) 431–435
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Development of the plasma operational regime in the large helical device by the various wall conditioning methods

K. Nishimura *, N. Ashikawa, S. Masuzaki, J. Miyazawa, A. Sagara, M. Goto, B.J. Peterson, A. Komori, N. Noda, K. Ida, O. Kaneko, K. Kawahata, T. Kobuchi, S. Kubo, S. Morita, M. Osakabe, S. Sakakibara, R. Sakamoto, K. Sato, T. Shimozuma, Y. Takeiri, K. Tanaka, O. Motojima, LHD Experimental Group

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

Abstract

Experiments in the large helical device have been developing since the first discharge in 1998. Baking at 95 °C, electron cyclotron resonance discharge cleaning, glow discharge cleaning, titanium gettering and boronization were attempted for wall conditioning. Using these conditioning techniques, the partial pressures of the oxidized gases, such as H_2O, CO and CO_2, were reduced gradually and the plasma operational regime enlarged. The glow discharge cleaning with the various working gases, such as hydrogen, helium, neon and argon, was effective in increasing the plasma purity. By this method, we obtained a central ion temperature of 10 keV. Boronization, which was started from FY2001, was also effective in reducing the radiation losses from impurities and in enlarging the density operational regime. We obtained a plasma stored energy of 1.31 MJ and an electron density of $2.4 \times 10^{20}\ m^{-3}$.

PACS: 81.15; 52.25; 52.50; 52.25.V
Keywords: Boronization; LHD; Neon; Recycling; Density limit

1. Introduction

The large helical device (LHD) is a superconducting heliotron device with $l = 2/m = 10$ continuous helical coils and three pairs of poloidal coils. The major and the averaged minor radii are 3.9 m and 0.65 m, respectively. The maximum magnetic field strength is about 3 T [1].

Plasma experiments have been progressing since the first discharge in 1998. These developments have been supported by increases in heating power, improvements in plasma facing materials, and progress in wall conditioning. In the first experimental campaign, wall baking at 95 °C before the start of the campaign, electron cyclotron resonance discharge cleaning (ECR-DC) and titanium gettering were used for wall conditioning. Titanium gettering was effective in reducing the oxygen related impurities and the hydrogen recycling. Using

* Corresponding author. Tel.: +81 572 582169; fax: +81 572 582618.
E-mail address: nisimura@lhd.nifs.ac.jp (K. Nishimura).

0022-3115/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2004.10.152

these techniques, the partial pressures of the oxygen containing gases, such as H_2O, CO and CO_2, were reduced gradually [2]. With the reduction of these gases, enlargement of the plasma operational space was observed. In 1999, carbon divertor plates were installed. As a result, significant reduction of radiation from metallic impurities (Fe, Cr and Ni) was observed [3]. However, radiation from oxygen increased [4]. Routine discharge cleaning (DC) was indispensable for reducing radiation from impurities and for enlarging the plasma operational regime. To reduce the recycling of specific gases, glow discharge cleaning (G-DC) with the various working gases, such as hydrogen, helium and neon, was started from 2002. This method was effective in increasing the plasma purity. Using this method, we obtained a central ion temperature of 5 keV in 2001 and 7 keV in 2002. Boronization, which was started from FY2001, was effective in reducing the radiation losses from oxygen, carbon and metals and in enlarging the density operational space. We obtained a plasma stored energy of 1.31 MJ and an electron density of 2.4×10^{20} m^{-3} in FY2003.

This paper reports the development of the plasma operational regime in reference to the wall conditionings.

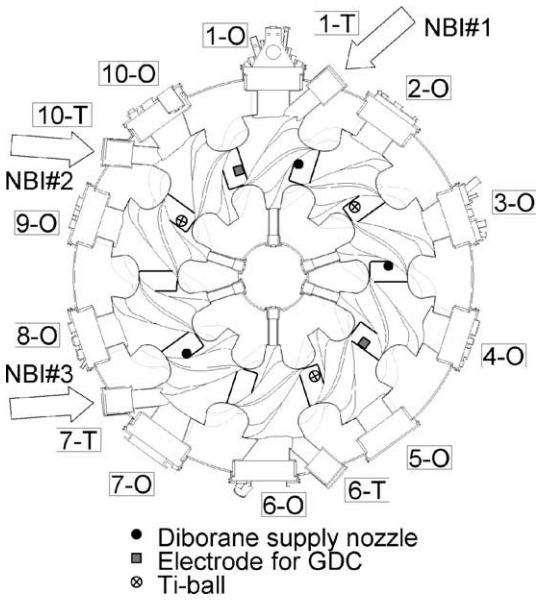

Fig. 1. Schematic view of LHD. Port names, three diborane supply nozzles, two electrodes for GDC, three titanium ball heads and three NBI ports are shown.

2. Wall conditioning

2.1. Setup of LHD for conditioning

The LHD vacuum vessel is made of SUS316L, and the total surface area including ports is 780 m^2 [5]. Water cooling channels were welded on the surface of the vessel to keep the temperature below 70 °C during coil excitation and to heat the vessel to 95 °C for baking. Most of the surfaces were covered with the SUS316L with Cu clad panels to keep the vessel temperature below 70 °C under 3 MW of steady-state plasma operation.

In the first and second campaigns, the facing material for the divertor plasma was SUS316L. Before the start of the third campaign, these materials were replaced with the cooled graphite plates (IG430U) [6].

Many devices for wall conditioning were installed to the LHD vessel. Fig. 1 shows the schematic view of the LHD with this equipment, such as three diborane supply nozzles, two movable electrodes for GDC and three titanium ball heads. Presently three neutral beam injectors (NBIs) are available with 4 MW injection power each. Many small sample probes are installed inside the vessel to investigate the surface conditions.

2.2. Baking and titanium gettering

Since the vacuum vessel of LHD is close to the helical coil cans, the baking temperature was restricted below 95 °C in order to maintain stable operation of superconducting system. In spite of the relatively low baking temperature, this mild baking is effective in degasing the surface of the vacuum vessel. About 50 molecular layers of surface adsorbates are expected to be evacuated by the 10 day bake before the start of plasma experiments [2,5].

Titanium gettering was also applied for further reduction of the oxygen impurity and for reduction of hydrogen recycling in the early stage of each experimental campaign. About 30% of vacuum vessel wall is expected to be covered with titanium film, and its thickness is expected to be more than three monolayers after 1 h operation. Since the heliotron configuration is free of current disruptions, wall conditioning improves smoothly.

2.3. Glow discharge cleaning with various gases

ECR-DC using 2.45 GHz/5 kW microwave source was used in combination with titanium gettering during the first experimental campaign. It showed good performance for the ECR-heated plasmas in the first experimental campaign [2,5]. After the second experimental campaign, focus of the experiments moved to the NBI and ion cyclotron range of frequency (ICRF) heating experiments. Wall conditioning of a wide area including NB injection ports and ICRF antennas was required. GDC with helium was begun to meet this requirement. Although GDC cannot be applied between shots be-

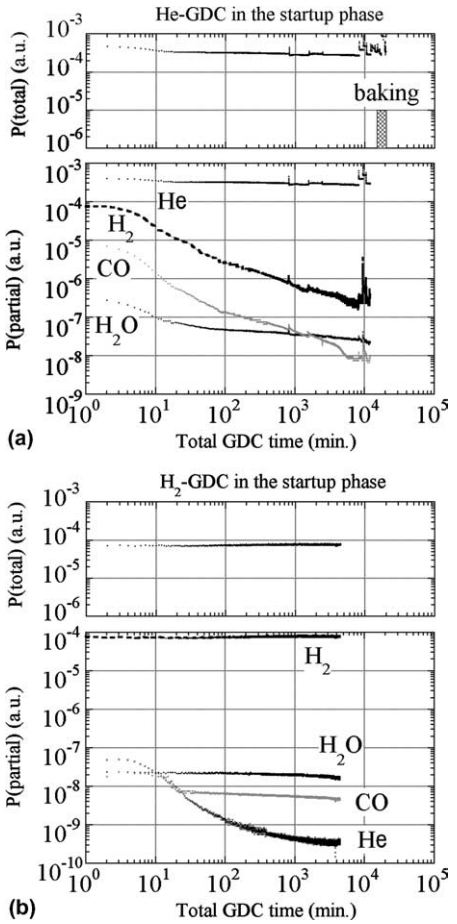

Fig. 2. Time evolutions of the partial pressures of He, H_2, CO and H_2O during (a) He-GDC in the 6th experimental campaign, and (b) H_2-GDC in the seventh experimental campaign.

cause of the steady magnetic field, GDC every night improved the wall conditioning gradually. Fig. 2(a) shows the time evolution of the partial pressures of He, H_2, CO and H_2O during the He-GDC in the sixth experimental campaign. Surface contaminations C and O are mainly evacuated as CO.

In the hydrogen gas-puffing experiments, significant helium was observed during the discharge and helium became dominant after termination of hydrogen gas-puffing. To reduce the helium desorption during hydrogen discharges, H_2-GDC was applied before the hydrogen experiments. Reduction of helium by H_2-GDC is shown in Fig. 2(b). Reduction rate of helium in H_2-GDC is larger than that of hydrogen in He-GDC because the adsorbing energy of helium is lower than that of hydrogen.

Although He-GDC was a popular wall conditioning method, the formation of bubbles on material surfaces by He discharges was reported [7]. After formation of bubbles, the desorption of helium, which was contained in the bubbles, continued until all the bubbles are broken. To avoid the formation of bubbles, Ne-GDC was attempted. Fig. 3 shows the time evolutions of the partial pressures of He, H_2, CO and H_2O during Ne-GDC. Ne-GDC before the start of plasma experiments was carried out in combination with baking (Fig. 3(a)). The reduction rates of H_2 and CO after the termination of baking are much larger than those in He-GDC (cf. Fig. 2(a)). It shows that Ne-GDC can improve the wall conditioning faster than He-GDC. Further research is needed on Ne-GDC, for instance with respect to damage of the wall and after effects during the plasma discharges.

Since the NBIs of LHD were optimized for high density operation ($>3\times10^{19}$ m^{-3}), the beam energy was relatively high (>160 keV). In the low-density (high temperature) discharges of hydrogen, shine-through loss

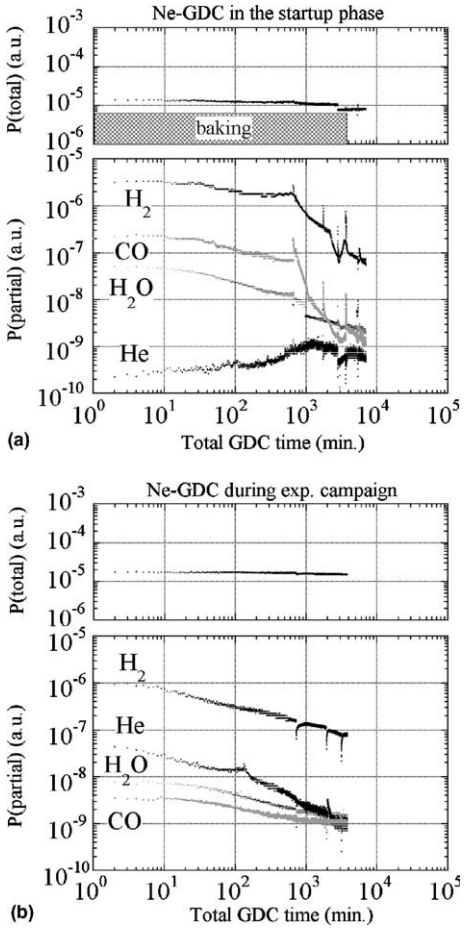

Fig. 3. Time evolutions of the partial pressures of Ne, H_2, He, CO and H_2O during Ne-GDC: (a) before the start of plasma experimental campaign, (b) three days of GDC during experimental campaign.

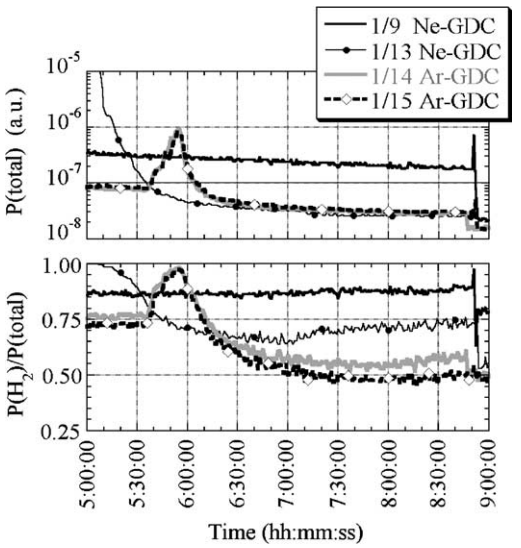

Fig. 4. Change of the H_2 concentration after Ne-GDC and Ar-GDC.

of the beam was large and, as a result, the absorbed power was low. To increase the power absorbed by the ions, high Z discharges were planned. The high-Z plasmas, however, tended to be diluted with the hydrogen adsorbed from the wall during the discharges. Because hydrogen was evacuated in Ne-GDC (Fig. 3(a)), GDC with heavier gases like neon and argon was attempted to reduce hydrogen recycling. Fig. 3(b) shows the time evolutions of the partial pressures of He, H_2, CO and H_2O during three days of Ne-GDC in the seventh experimental campaign. Reduction of hydrogen is observed to be similar to that using Ne-GDC before the campaign (Fig. 3(a)). Fig. 4 shows the change of the H_2 concentration after Ne-GDC and Ar-GDC. H_2-GDC was continued from January 6 (2004) to the morning of January 9, and GDC with the heavier gases was conducted for 63 hours (from the night of 9–13 January) with neon and 11 h (14 and 15 January at night) with argon. The concentration of H_2 on January 9 was reduced by half by January 15 after GDC with the heavier gases (Ne and Ar). The highest ion temperature in LHD was recorded in January 15; an ion temperature of 10 keV (ArXVII), electron temperature of 4.2 keV (ECE), and averaged electron density of 0.4×10^{19} m^{-3} were measured using injected NB power of 12.5 MW, of which 3.7 MW was absorbed.

2.4. Boronization

To reduce impurity release from the chamber wall, boronization (boron coating) using diborane (B_2H_6) at room temperature without wall baking was started from FY2001 (fifth experimental campaign). At the beginning of the boronization, one nozzle was used to supply diborane, and two more nozzles were installed to increase the coated area in FY2002 (sixth experimental campaign) [8].

Diborane was introduced into a helium GD plasma without wall baking. The introduced diborane was easily decomposed into boron and hydrogen. Most of the hydrogen was exhausted, and boron was coated on the vacuum vessel wall with residual hydrogen. After boronization, He-GDC was used for three hours to reduce decomposed hydrogen in the boron film. By this coating, oxygen was trapped into the boron film and kept in the form of boron oxide. Other contaminations on the vacuum vessel were covered with the boron film and their release from the wall was suppressed.

During the sixth and seventh experimental campaign, boronizations were carried out three times for 7 h each. The thickness of 30–50 nm and the coated area of 60% of the vacuum vessel were estimated [8]. After boronization, the oxygen concentration was reduced to less than 1% of the level found in pre-boronization discharges of similar density and input power. The carbon levels were reduced to 50–70% of the pre-boronization levels. As a result, radiation loss decreased about 30–50% and the operational density limit increased. Fig. 5 shows the operational regime of the electron density and the plasma stored energy before and after boronization. Solid circles are the data before boronization and open circles after boronization under the experimental conditions of $R_{ax} = 3.6$ m, $B_T = 2.75$ T, $P_{NBI} = 6$–8 MW. Broken lines show the accessible operational boundaries. Enlarge-

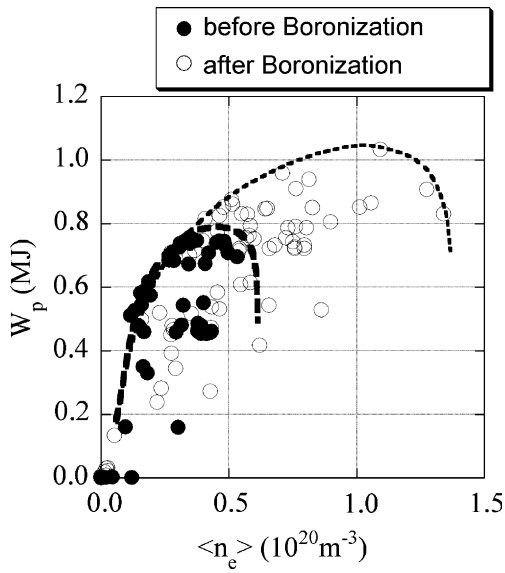

Fig. 5. Operational regime of electron density and plasma stored energy before (●) and after (○) boronization. Broken lines show the accessible operational boundaries.

ment of the operational regime to higher densities was observed after boronization.

Together with the increase in the heating power and these wall conditionings, we obtained plasma stored energy of 1.31 MJ (at $\langle n_e \rangle = 1.0 \times 10^{20}\ m^{-3}$), and an averaged electron density of $1.6 \times 10^{20}\ m^{-3}$ (at W_p = 0.6 MJ) by gas puffing and $2.4 \times 10^{20}\ m^{-3}$ (at W_p = 1.0 MJ) by pellet injection.

To investigate the details of the wall conditionings, many sample probes were installed at various positions of the LHD vacuum chamber. The analyzed result shows that oxygen is trapped in boron film during boronization and the boron surface works well as an oxygen getter during plasma experiments.

3. Summary

Wall conditioning has been conducted using mild temperature baking at 95 °C, EDR-DC, GDC with various gases and boronization. GDC with the gas being used in the subsequent plasma experiments is effective in keeping ion purity during plasma experiments. Ne-GDC before the series of plasma experiments was effective in reducing the conditioning time; however, further research is needed into its characteristics. Boronization is also effective in reducing impurity release and radiation losses caused by the impurities. By these wall conditionings, we attained a central ion temperature of 10 keV, a plasma stored energy of 1.31 MJ and an averaged electron density of $1.6 \times 10^{20}\ m^{-3}$ by gas puffing and $2.4 \times 10^{20}\ m^{-3}$ by pellet injection.

In order to improve the good wall condition to get higher plasma performance, further PSI studies are required.

Acknowledgments

The authors would like to thank Mr N. Suzuki for providing the data of mass-spectrometer and technical staff for operation and maintenance of LHD.

References

[1] A. Iiyoshi et al., Nucl. Fus. 39 (1999) 1245.
[2] A. Sagara et al., J. Plasma Fus. Res. 75 (1999) 263.
[3] B.J. Peterson et al., J. Nucl. Mater. 290–293 (2001) 930.
[4] S. Morita et al., Phys. Scr. T 91 (2001) 48.
[5] S. Masuzaki et al., J. Nucl. Mater. 290–293 (2001) 12.
[6] Y. Kubota et al., Fus. Eng. Des. 39&40 (1998) 247.
[7] M. Miyamoto et al., J. Nucl. Mater. 329–333 (2004) 742.
[8] K. Nishimura et al., J. Plasma Fus. Res. 79 (2003) 1216.