Removal of tritium from vacuum vessel by RF heated plasmas in LHD

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Abstract

The tritium removal from the vacuum vessel is one of the key issues for the realization of a fusion reactor. As in-situ tritium removal techniques from the plasma facing materials, helium glow discharge wall conditioning (GDWC) and RF heated plasma due to electron cyclotron wall conditioning (ECWC) and ion cyclotron wall conditioning (ICWC) are applied with Large Helical Device (LHD) which remains tritium produced by deuterium plasma experiment. As the result, it suggests that ICWC could remove the tritium more efficiently than the ECWC and the GDWC. In the ICWC operation, the high energy particles induced by the minority ion heating mode as the standard ICRF heating operation may play an important role in tritium removal from the plasma-facing materials due to the particle's bombardment.

Keywords: tritium removal, RF heated plasma, electron cyclotron wall conditioning, ion cyclotron wall conditioning, glow discharge wall conditioning, deuterium plasma experiment

1. Introduction

It is an urgent problem to develop new energy sources that can substitute for fossil fuels. As one of the new energy sources, the research of nuclear fusion is being progressed. To realize the nuclear fusion reactor on the earth, high-temperature plasma using deuterium (D) and tritium (T) as fuel must be confined in the vacuum vessel by a magnetic field, and then confined plasma is heated by the neutral beam injection and the radio-frequency (RF) systems to achieve more high temperature [1]. Since tritium is a radioactive isotope and its natural abundance is extremely low, it is indispensable to remove and recover unburned tritium from the vacuum vessel [2]. Therefore the development of in-situ tritium removal techniques would be one of the key issues for the realization of a fusion reactor. As in-situ wall conditioning techniques for the tritium removal from the plasma facing components, normal plasma operation, vacuum vessel wall baking, glow discharge wall conditioning (GDWC) using helium and hydrogen (H, D), oxygen-containing GDWC, and RF heated plasmas such as electron cyclotron wall conditioning (ECWC) and ion cyclotron wall conditioning (ICWC) have been applied with various types of fusion test device, TEXTOR, JET, TFTR, JT-60U, ASDEX-U, TCV, W7-X and LHD [3-19]. These wall conditioning operations are expected to remove tritium from the divertor tiles and the first wall in the vacuum vessel.

In the deuterium plasma experiment using a large fusion test device, a small amount of tritium is produced by the D-D reaction. It can be used as a tracer to investigate the tritium removal performance because a part of produced tritium is implanted and remained in the vacuum vessel wall. Since 2017, Large Helical Device (LHD) which has a helical type superconducting magnet coils, is in the regular operation of

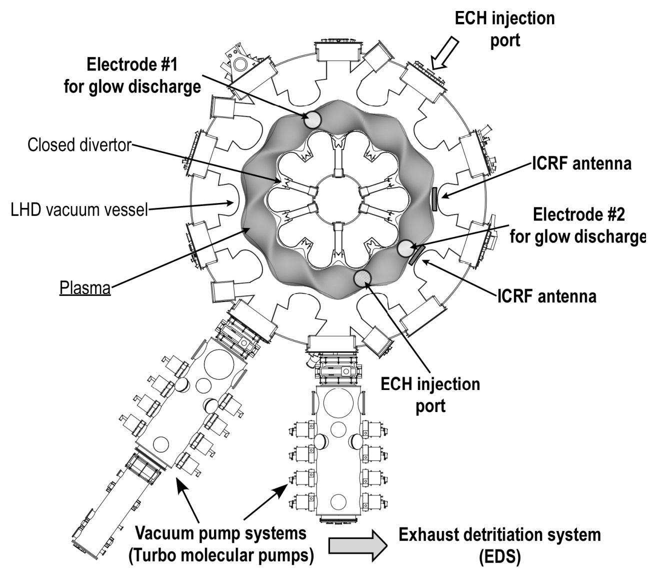

Fig. 1 Schematic diagram of LHD: 2 electrodes for glow discharge, RF heating systems, vacuum pump systems, vacuum vessel.

Table 1 Tritium inventory in LHD before the experiment and the discharge conditions of GDWC, ECWC and ICWC.

Estimated tritium inventory in LHD before plasma experiment [GBq]		9.5	
He glow discharge	Voltage [V]	218~272	
	Current [A]	30	
	Pressure [Pa]	1.0~1.3	
	Operation time [h]	2	
RF heated plasma	B [T]	2.75	
	R [m]	3.6	
	Opeartion gas	He	
	Total imput energy [GJ]	ECH: 1.6	ICH: 3.7
	n_e [10^{19} m^{-3}]	~ 1.0	~ 1.5
	T_e [keV]	~ 6	~ 2
	T_i [keV]	~ 2	~ 2
	Number of shot	58	54
	Discharge time [s]	~37	
	Discharge period [s]	210	
	Total discharge time [h]	0.60	0.56

producing deuterium plasma for experiments [20, 21]. The exhaust behavior and inventory of tritium in LHD have already been investigated and an increase of several GBq in tritium inventory was noticed during deuterium plasma operation [22-25]. Then the tritium inventory increased with deuterium plasma operation to several GBq. In this study, we focus on the tritium release behavior in the exhaust gas and report the initial results of tritium removal performance from the LHD vacuum vessel by RF heating helium plasmas.

2. Experimental setup and procedure

2.1 LHD system and the exhaust gas monitoring

The schematic diagram of LHD is shown in Fig. 1. The LHD is equipped with two types of RF heating devices: electron cyclotron heating (ECH) systems via 4 ports and ion cyclotron heating (ICH) systems by using a pair of antennas installed in two locations. For GDWC, two electrodes were installed at the opposite port on the trous. As plasma-facing materials, stainless steel is used for the first wall and carbon material is used for the divertor plates. In this study, five TMPs were used to maintain the base pressure in the vacuum vessel, and high-temperature plasma was triggered by injecting helium gas into the vacuum vessel and heating it with RF. The exhaust gas from LHD was fed into the exhaust detritiation system (EDS) [26] to recover exhausted tritium as shown in Fig. 2. The dry nitrogen gas was fed into the outlet of the vacuum pump system to purge the tritium in the piping, and this results in a gas flow rate of 7~10 Nm^3/h at the inlet of EDS and dew point in the exhaust detritiation system less than 238 K (< 300 ppmv). The exhaust gas compositions at the inlet of EDS were analyzed with a gas chromatography system (Agilent, 490MicroGC), tritium monitor using a proportional counter (Berthold Technologies, LB110), and an original water bubbler system (WBS) with chemical form discrimination [27].

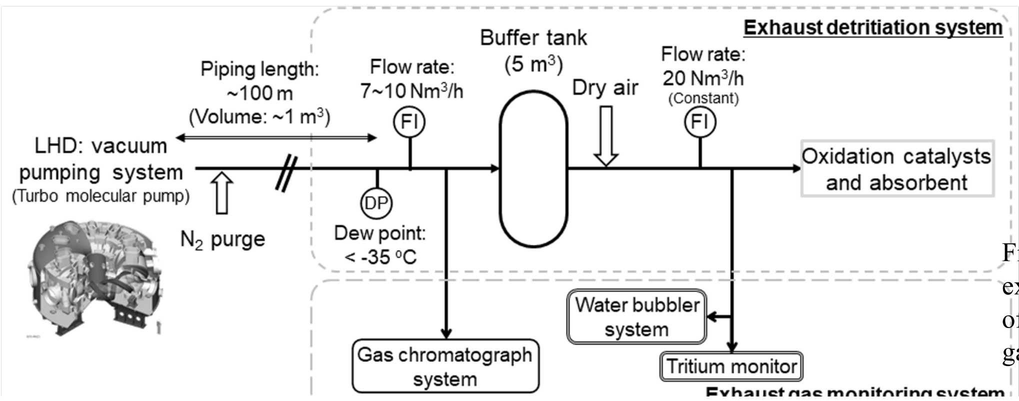

Fig. 2 Flow diagram of exhaust gas line, a part of EDS and the exhaust gas monitoring devices.

2.2 Operation condition and procedure

The operation condition for GDWC, ECWC, ICWC is summarized in Table 1. The tritium inventory in LHD before the operations were estimated to be 9.5 GBq. The tritium inventory in the LHD vacuum vessel was estimated by subtracting the amount of tritium produced by the D-D fusion reaction and the amount of tritium measured at the inlet of the EDS. The amount of tritium decay was also incorporated in the estimation of the tritium inventory [23]. The produced tritium amount was estimated from the measurement of the neutron. The uncertainty of the neutron measurement was estimated to be about 10% on the calibration factor [28]. The uncertainty of the amount of tritium measurement was estimated to be a few %. In GDWC operation with helium gas, a constant current of 30 A was maintained for two hours. For the RF heated plasma operation, the magnetic field was set to be 2.75 T. The electron cyclotron heating frequencies were 77 and 154 GHz, and the ion cyclotron heating frequency was 38.47 MHz. In ion cyclotron heating in helium plasmas, it has been confirmed that the RF heating power is absorbed by hydrogen ions in the minority ion heating regime, and higher energy particles are produced [28, 29]. Each discharge time was about 37 seconds, and the discharge operation was repeated in 210-second periods. The total discharge time accumulated each discharge time was about 0.6 hours for ECWC and about 0.56 hours for ICWC, respectively.

As the procedure for tritium removal operation, the GDWC was performed first at midnight, followed by ICWC and ECWC. The operation was paused for about 1 hour between ICWC and ECWC to purge the exhausted tritium.

3. Results and discussion

3.1 Discharges for ICWC and ECWC

Typical discharges of ICWC and ECWC are shown in Fig. 3. During the discharge, the plasma parameters such as electron density, electron temperature, and ion temperature were almost stable. The total radiation loss in the ICWC operation was about 1.8 times higher than that in the ECWC

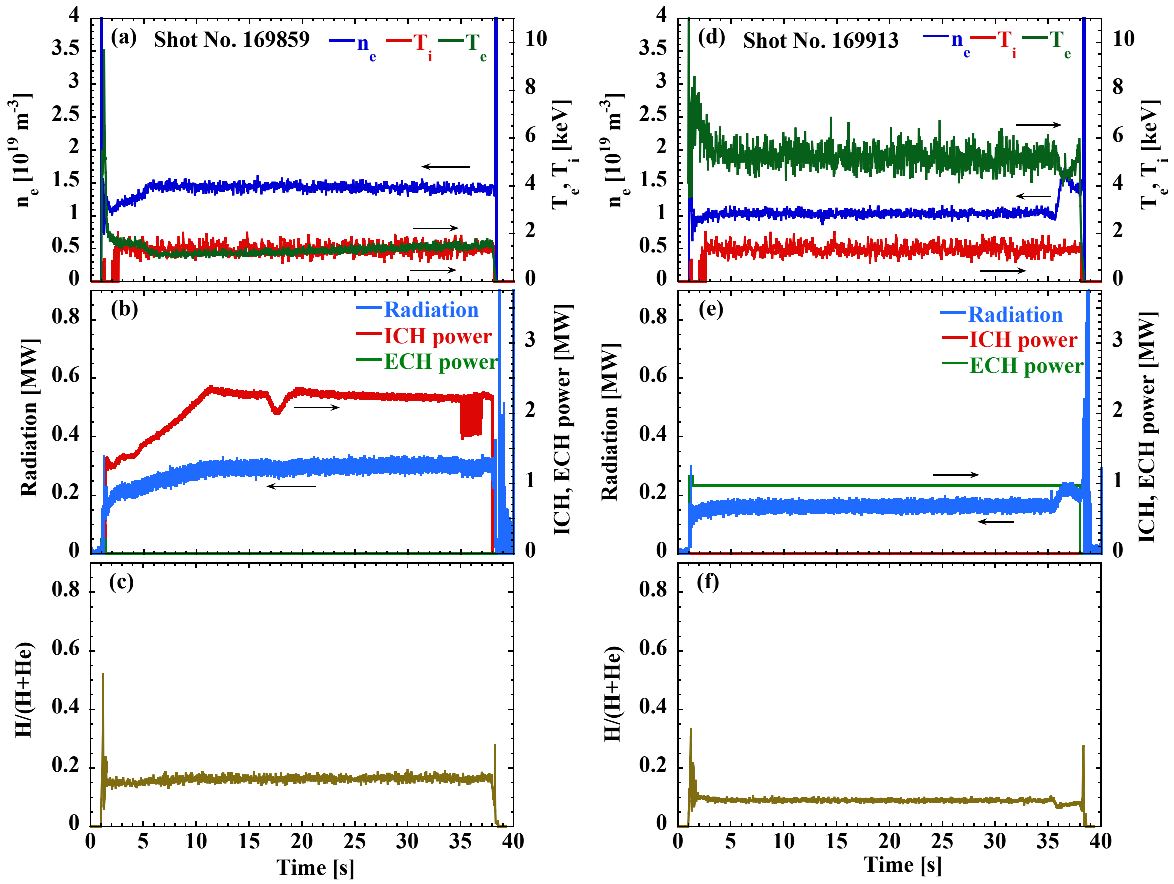

Fig. 3 Typical discharge (left: ICWC, right: ECWC); (a) and (d): electron density, electron temperature and ion temperature, (b) and (e): total radiation loss, ICH and ECH power, (c) and (f): the ratio of H and He in helium plasma.

operation. During the operation, hydrogen (H) was detected in the helium plasma by optical emission spectroscopy. The ratio of hydrogen as shown in Fig.3 (c) and (d) was calculated from the ratio of the emission line intensities of Hα (656.28 nm) and HeI (587.6 nm). The error of the measurement was estimated to be about 10%. The ratio of hydrogen in the helium plasma was about 1.8 times higher in the ICWC than in the ECWC. The discharge was repeated for 54 shots in ICWC and 58 shots in ECWC in 210-second cycles.

3.2 Tritium removal operation

The results of the tritium removal experiment due to GDWC, ECWC, and ICWC are shown in Fig. 4. The average

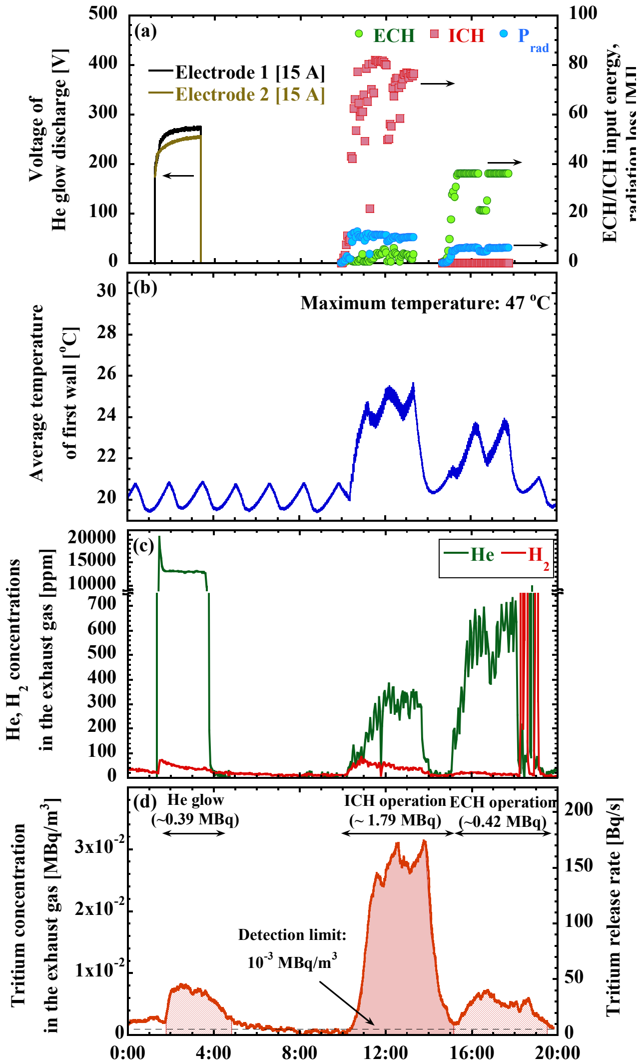

Fig. 4 The results of tritium removal operation; (a). Voltage of GDWC, radiation loss and the input energy of ICH and ECH, (b). Average temperature of first wall, (c). He and H_2 concentrations in the exhaust gas, (d). tritium concentration in the exhaust gas.

Table 2 Tritium release amount and average release rate

Operation	Total input energy	Total time	Tritium release amount	Average tritiur release rate
GDWC	0.06 GJ	2 h	0.39 MBq	5.4×10^1 Bq/s
ECWC	1.6 GJ	0.60 h	0.42 MBq	2.0×10^2 Bq/s
ICWC	3.7 GJ	0.56 h	1.79 MBq	9.0×10^2 Bq/s

temperature of the first wall in LHD as shown in Fig. 4(b) was measured by thermocouples installed on the backside of the first wall plates. The temperature fluctuation with a period of about 1.5~2 hours was induced by the temperature control of the cooling water.

3.2.1 Glow discharge wall conditioning. Helium GDWC operation was conducted before RF heated plasma operation. The applied voltage for glow discharge was about 250 V. During helium GDWC operation, molecular hydrogen (Q_2: Q=H, D, T) was released from the vacuum vessel wall and was observed in the exhaust gas as shown in Fig. 4(c). At the same time, the tritium concentration in the exhaust gas increased. Since there is no magnetic field in GDWC, it is considered that the helium ions accelerated by the applied voltage bombarded the whole vacuum vessel wall. Then the molecular hydrogen (H_2) and the tritiated hydrogen (HT) would be released from the plasma-facing materials.

3.2.2 RF heated plasmas by ICWC and ECWC. The total input energy in the operations of ECWC and ICWC were 1.6 GJ and 3.7 GJ, respectively. As shown in Fig. 3(b), the total radiation loss in the ICWC operation was larger than that in the ECWC operation. As a result, the average first wall temperature during the ICWC operation would be higher than that during the ECWC operation. The tritium released by the temperature rise of the vacuum vessel wall was often observed as a chemical form of water vapor. However, as the results of the chemical form discrimination measurement by WBS, it is confirmed that tritiated hydrogen (HT) is the dominant chemical form of tritium in the exhaust gas. Therefore, the amount of tritium released due to the temperature rise is considered to be negligible in these operating conditions. In addition, hydrogen (H) was detected in the helium RF heated plasma as shown in Fig. 3, and thus a small amount of hydrogen gas was also observed in the exhaust gas. These observation results also support the chemical form of tritium in the exhaust gas. Since a magnetic field is required in RF heated plasmas, the heated plasma flows into the divertor plates along the magnetic field lines. Therefore the tritium could be mainly released from the divertor tiles in RF heated plasma. The amount of tritium released by the ICWC was estimated to be about 1.8 MBq, which was about 4.3 times larger than that by the ECWC. Thus the ICWC operation could enhance the release of tritiated hydrogen (HT). On the other hand, the amount of tritium released by the ICWC is about 0.02% of the tritium inventory in LHD, and the order of operations of ICWC and ECWC may have little effect on the difference in tritium release between ICWC and ECWC.

3.2.3 Comparisons of tritium removal performance.

The tritium release amount and rate are summarized in Table 2. The tritium release amount by GDWC was about 0.39 MBq, which is the same as the results of the ECWC operation, and the average tritium release rate, which was determined by dividing the tritium release amount by the total discharge time, was estimated to be about 50 Bq/s. In the ECWC operation, the average tritium release rate was about 200 Bq/s, because the total discharge time was about a quarter of that in the GDWC operation. In the ICWC operation, the average tritium release rate was enhanced up to close to 1000 Bq/s. Although the total input energy of the ICWC operation was about 2.3 times larger than that of the ECWC operation, the tritium release rate was enhanced more than 4 times. It is known that high energy particles are produced in the minority ion heating regime by ICH and irradiates the divertor tiles. A part of them escapes out of the plasma via a charge exchange process. [29, 30]. Thus the high energy particles induced by ICH bombard the vacuum vessel wall and may play an important role in tritium removal from plasma-facing materials.

4. Conclusions

We evaluated several in-situ tritium removal techniques for residual tritium in Large Helical Device where deuterium plasma experiments are conducted. As tritium removal techniques, glow discharge wall conditioning (GDWC) without a magnetic field, ion cyclotron wall conditioning (ICWC), and electron cyclotron wall conditioning (ECWC) with a magnetic field were exercised. Among GDWC, ECWC, and ICWC operations of the LHD, the ICWC operation showed the highest average tritium release rate and the tritium release rate in ICWC operation was better than that of GDWC. In ICWC operation, the high energy particles are produced by heating mechanism and continuous bombardment of those on the surface of plasma-facing materials can yield efficient desorption of tritium leading to enhanced total recovery and release rate as well. The results suggest that the ICWC operation could remove the tritium more efficiently than the other operations.

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