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# Wall Conditioning at The Starting Phase of LHD

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## Abstract

The first results on wall conditioning in the first and second campaign of LHD experiments are described. By confirming device integrity, operational reliability, and environmental safety, LHD has been successfully started up with intensive discharge cleaning without doing high-temperature baking. Evacuation of about 100 molecular layers of surface contaminants is found to be the key to start up the target plasma by ECH for NBI injection. Importance of combination between mild baking, GDC, ECR-DC and main shots is experimentally confirmed.

Key words : wall conditioning, ECR-DC, GDC, glow discharge, LHD, getter, baking

## I. Introduction

After the 8-years of construction with many R&D studies, the Large Helical Device (LHD) experiments have started and successfully produced the first plasma on schedule on March 31, 1998 [1]. In the first experimental campaign, the operational integrity of the all superconducting coil machine has been carefully confirmed. And then, the 2nd harmonic 84 GHz ECH plasmas at 1.5T have been successfully generated as target plasmas for NBI heating in the next campaign[2]. After 2-months work in the vented vacuum vessel, the second campaign has started in the middle of September, 1998, by focusing on generation of NBI heated plasmas [3].

In this starting phase of LHD, the main purpose of wall conditioning has been to reduce oxygen impurities in order to suppress the radiation loss power under ECH up to 400kW.

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For this requirement, intensive discharge cleaning has been mainly carried out without baking at high temperatures around 300°C, because the temperature of the plasma vacuum vessel is limited below 100°C due to the cryogenic capability for the superconducting magnets [4]. For large plasma machines such as LHD, which has the major radius of 3.9m and the in-vessel surface area of about 780m$^2$, wall conditioning without baking at high temperatures is quite desirable to minimize not only the heat load on cryogenics systems but also thermal deformation and stress of the vacuum vessel and the total utility for baking.

This paper reports the first results on wall conditioning in LHD. The conditioning scenario preliminary perfomed in these campaigns can be further improved in the next series of LHD experiments, and contributes on establishing wall conditioning techniques without baking at high temperatures.

## II. Wall conditioning in the first campaign

### *2.1 Evacuation of surface contaminants*

The plasma vacuum vessel made of 316 stainless steel with the 78tons of weight has the total volume of 210m$^3$, and the degreased inner surface of 780m$^2$ has been cleaned with acid, then with demineralized water and finally with alcohol. The toroidal vessel is connected to the horizontal manifold with the diameter of 1.2m and length of 10m, which is equipped with two cryogenic pumps of 70x2m$^3$/s for water, two turbomolecular pumps of 5.5x2m$^3$/s for $N_2$ and two compound pumps of 1.8x2m$^3$/s for $N_2$. At the side of the manifold far from the high magnetic field area, there are located pressure gauges and a differentially pumped quadrupole mass analyzer. After finishing the helium leak test, the pressure of the plasma vacuum vessel has reached 9x10$^{-7}$ Pa at the end of March, 1998.

On March 28, soon after the coil excitation tests up to 1.5T, ECR discharge cleaning (ECR-DC) with He was carried out using the 2.45 GHz micro-wave in the 875 G standard confining configuration, without baking the vacuum vessel. Figure 1 shows the remarkable gas burst of mainly CO, $H_2$ and $H_2O$ due to the first discharge with 3kW. By increasing the effective pumping speed from 1 to 10 m$^3$/s and decreasing the ECR power, the controllable steady discharge has been achieved. Next day, by changing the working gas to $H_2$, ECR-DC has been continued with gradually increasing the input power up to 10kW. During this operation, several tests have been carefully carried out from safety aspects by measuring the micro-wave leakage and the temperature rise of the vacuum vessel, which is cooled with water. Figure 2 shows the total evacuated amounts of main gases as a function of discharge time, while the out gassing rate is largely varied under these various test operations of ECR-DC. As the result of these treatments, about 665Pam$^3$ of CO and $H_2O$ gases was evacuated, which was about 2.3x10$^{20}$ molecules/m$^2$ averaged on the geometrical surface area of about 780m$^2$, that is, about 10 molecular layers.

As the beginning of the first campaign, on March 31, the first heated plasma was successfully ignited at 1.5T with ECH of 150kW for 60ms. Then the 5kW ECR-DC was intensively repeated for the total of 380h. Figure 3 summarizes the result of ECR-DC in the first campaign, where it is observed that, by evacuating about 100 molecular layers of $H_2O$ and CO formed from surface contaminants with ECR-DC, the maximum plasma stored energy attained after each conditioning has remarkably increased up to 15kJ. Figure 4 shows that this tendency coincides well with decrease of the maximum radiation loss power under the progress of wall conditioning. These results are mostly attributed to decrease of impurity influxes of such as O and C from the plasma facing wall. In fact, as shown in Fig.5, where the gas efficiency defines the ratio of averaged plasma density to electron density supplied by gas-puffing, the gas efficiency changes from a large number to unity with the increase of shot number. This result means that the dominant gas source for sustaining plasmas clearly changed from the internal wall-contaminants such as C and O to the external gas-puffing under the progress of conditioning, eventually resulting in good controllability of plasma density under the external gas-puffing.

### 2.2 *Titanium gettering and baking*

After starting the first campaign, 95°C baking was tried for 61h with confirming device integrity, where the cooling water for the plasma vacuum vessel was changed to the hot water heated at 300kW. The total pressure increased up to $1\times10^{-3}$Pa under the pumping of $10m^3/s$ and about $1070Pam^3$ of desorbed gas was evacuated, that is, about 16 molecular layers as shown in Fig.3. This result means that this mild baking is effective to degas the area which does not face the ECR plasma.

In order to reduce oxygen impurities as fast as possible at an early stage of the first campaign, titanium gettering was carried out. Toroidally distributed 3 movable Ti-heads were operated twice a day at B=0 for 1h each with the total sublimation rate of about 2g/h, covering the plasma-facing surface over 30% with more than 3 monolayers of Ti, which is the minimum thickness required to fully cover the substrate[5]. The total sublimation time was limited at 30h, at which the Ti film could be thicker than 10 μm around Ti-heads and expected to peel off according to our laboratory tests.

Figure 6 shows that the plasma stored energy increased sharply after the beginning of Ti-gettering. Concerning ECR-DC after Ti-gettering, since the Ti film absorbs $H_2$ up to H/Ti ratio of 1.5 to 2 by forming bulk $TiH_2$, helium gas was used instead of $H_2$ to sustain ECR-DC in order to avoid an excessive hydrogen recycling in main discharges. In this technique using He, desorbed hydrogen from stainless steel surfaces was used as the working gas to remove oxygen by forming $H_2O$. In fact, the color of ECR plasma gradually changed from HeI(587.6nm) dominated red to rather white due to desorbed gases at the early stage of the conditioning, and then, after evacuating more than 90 molecular layers of surface contaminants, the red colored plasma became stable without changing to white during ECR-DC. The color of He ECR plasma is a good measure of wall conditioning.

### 2.3 *Surface sample analyses*

After finishing the first campaign and opening the vessel to the air, surface samples have been under analyses using RBS, ERD, AES, TEM, SEM and EDS. Figure 7 shows the typical RBS spectrum taken on the graphite sample, which was located 1.25 helical pitch away from the nearest Ti-head and was exposed to the outer divertor plasma. It is observed that there is a deposited thin film, consisting of O, Fe, and Mo, where C is the base material and Mo is assumed to come from the trace element contained 2.1wt.% in 316 stainless steel of the vessel as well as Fe. There is not detected any Ti element by RBS, AES and EDS, suggesting that these detected metals are locally sputtered and redeposited ones [6]. This film has been preliminary identified with

TEM to be FCC austenite containing oxides and not a ferromagnetic film [7].

## III. Wall conditioning in the second campaign

### *3.1 Conditioning of wide areas*

Since the main program of the second campaign consists of NBI heating experiments and ICR heating tests [1], wall conditioning of wide areas has been required by covering NBI injection ports and ICRH antennas. For this purpose, glow discharge cleaning (GDC) using He was arranged by installing two sets of 50cm movable electrodes made of graphite.

After pumping down to an UHV condition, the plasma vacuum vessel was baked at 95°C for 240h, resulting in evacuation of about 53 molecular layers of surface adsorbates such as $H_2O$, CO and $CH_4$. Owing to this preparation, GDC operations could start without any severe arcings. The GDC operation condition has been set at He pressure of 0.75Pa under the pumping speed of about $2m^3/s$, the voltage around 210V and the current of about 14A for each electrode, that is, the total power of about 6kW.

Figure 8 shows that, under He GDC, surface contaminants C and O are mainly evacuated by forming CO, presumably because the temperature of the vacuum vessel is usually below 30°C or below 95°C even in case of baking [8]. In Fig.8 it is found that the total gas amount evacuated with baking and GDC is comparable to that in ECR-DC in the first campaign. In fact, the plasma stored energy with ECH could exceed 15kJ after evacuation of 100 layers in ECR-DC in the first campaign and 80 layers in GDC from the first day of ECH in the second campaign.

### *3.2 Maintenance of wall condition*

After starting high performance operations such as high-power, high-density or long discharges with NBI injections and $H_2$ pellet injections, outgases such as CO, $CO_2$ and $CH_4$ often increased shot by shot. In this situation, Ti-gettering was used again to increase the effective pumping speed. And the overnight GDC operation has been regularly carried out, resulting in good recovery of wall condition. These operations suggest that discharge cleaning is basically effective and necessary to improve and maintain the wall condition under combination with main shots.

## IV. Conclusion

LHD has required very careful but reasonably quick start-up procedures, including wall conditioning, by confirming device integrity, operational reliability, and environmental safety. Under these requirements, LHD has been successfully started up with discharge cleaning without doing high-temperature baking.

By quantitatively evaluating wall conditioning in the first and second campaign, it has been reproducibly found that evacuation of about 100 molecular layers of surface contaminants is the key condition to start up the target plasma by ECH for NBI injection. For this purpose, it is found that ECR-DC and GDC are almost comparable, but GDC is suitable in terms of wide area conditioning as well as baking. Prior to start discharge cleaning a mild baking is useful and sufficient to suppress un-controllable gas burst or severe arcing.

In order to improve and maintain the wall condition, discharge cleaning is effective under combination with main shots. For higher plasma performance in the next campaign, additional methods such as boronization are practically required.

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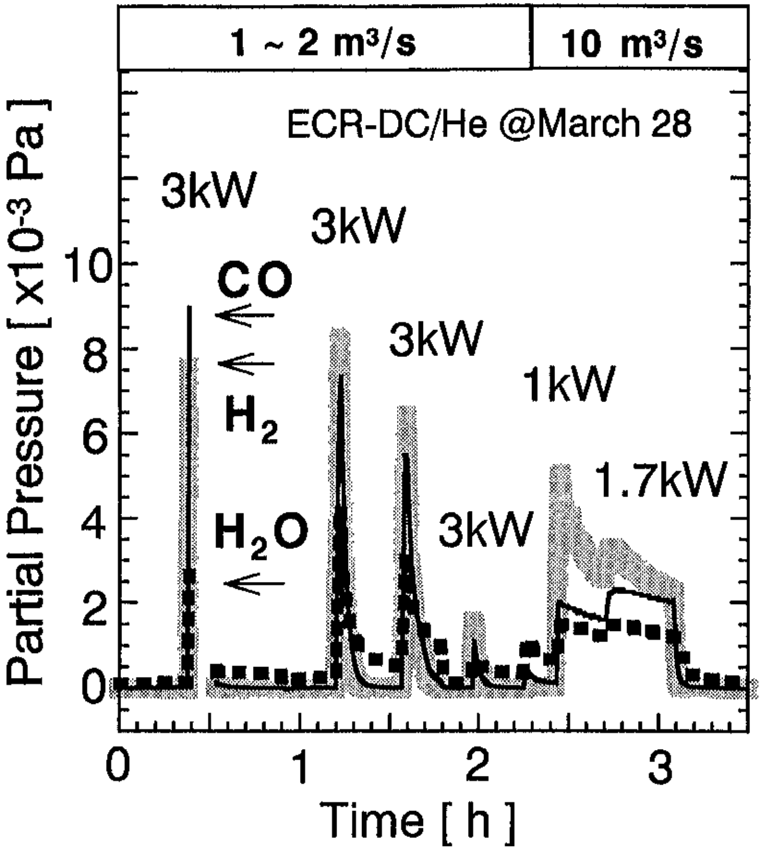

Fig.1 Gas desorption under the first ECR discharge cleaning in LHD.

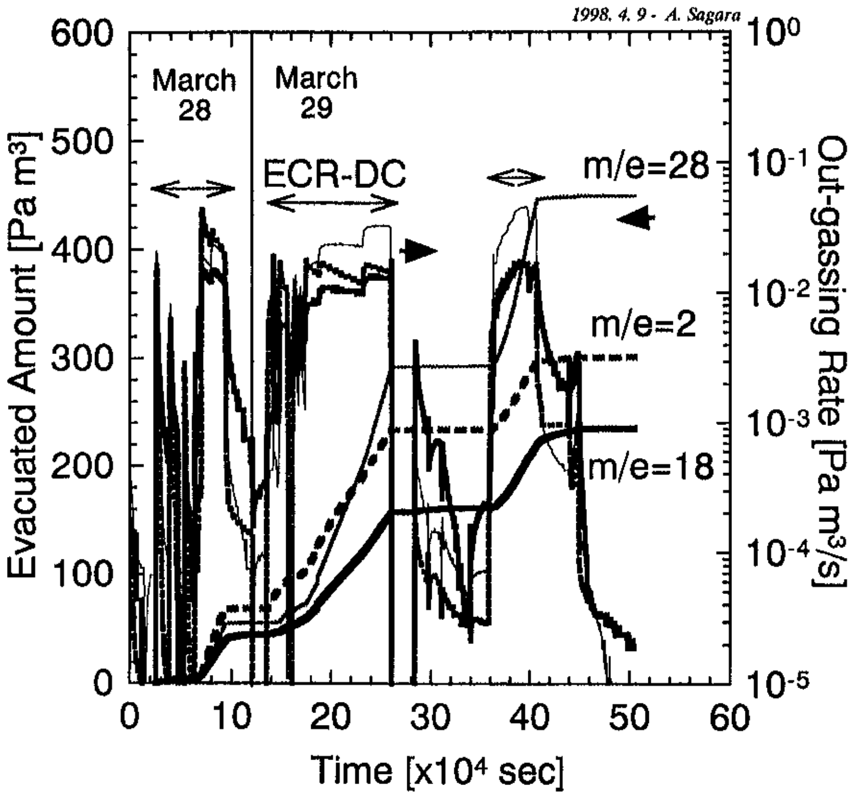

Fig.2 Outgassing and evacuation under various ECR-DC tests before the LHD first shot.

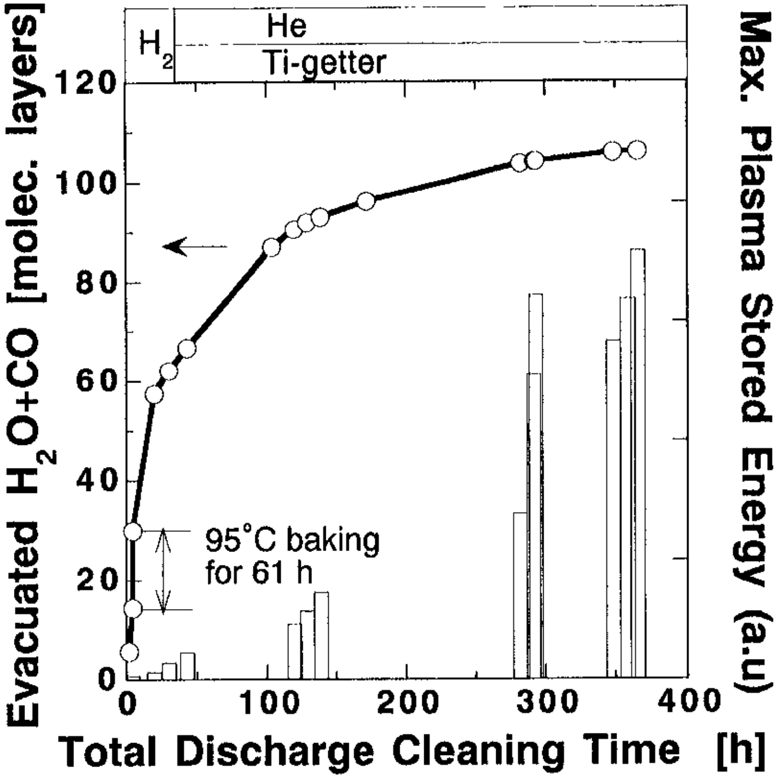

Fig.3 Results of ECR-DC in the first campaign of LHD.

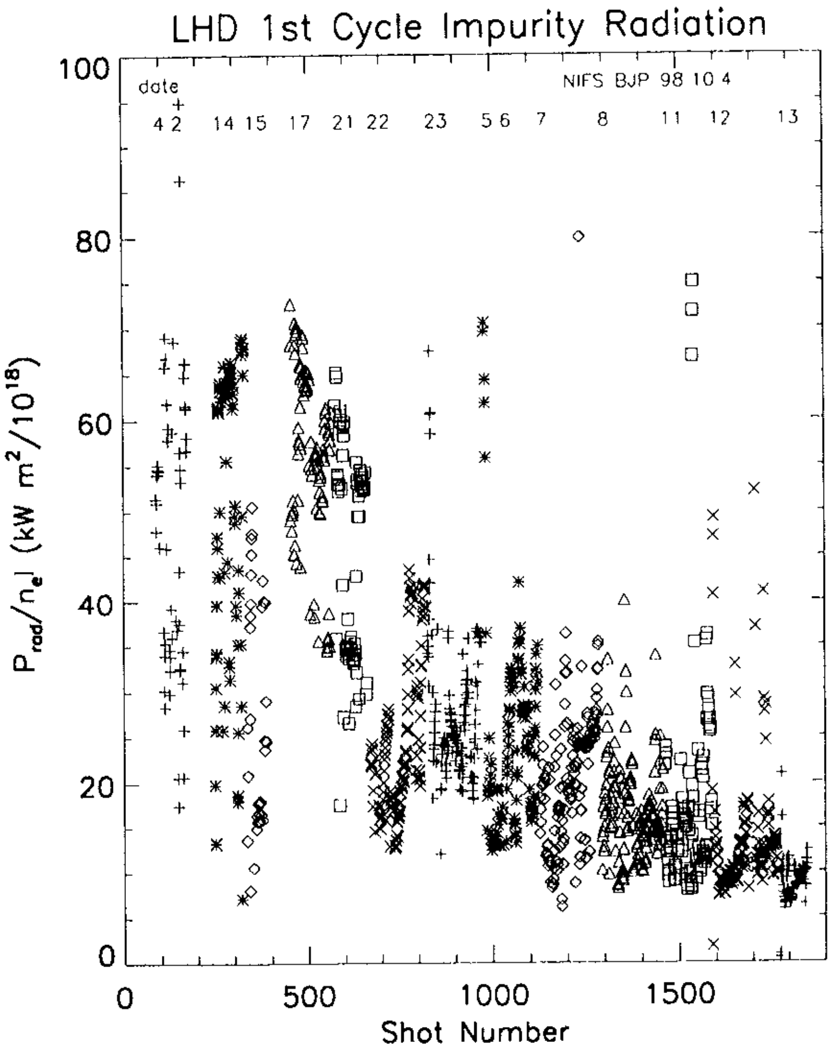

Fig.4 Radiation loss per density measured with bolometer in the first campaign of LHD.

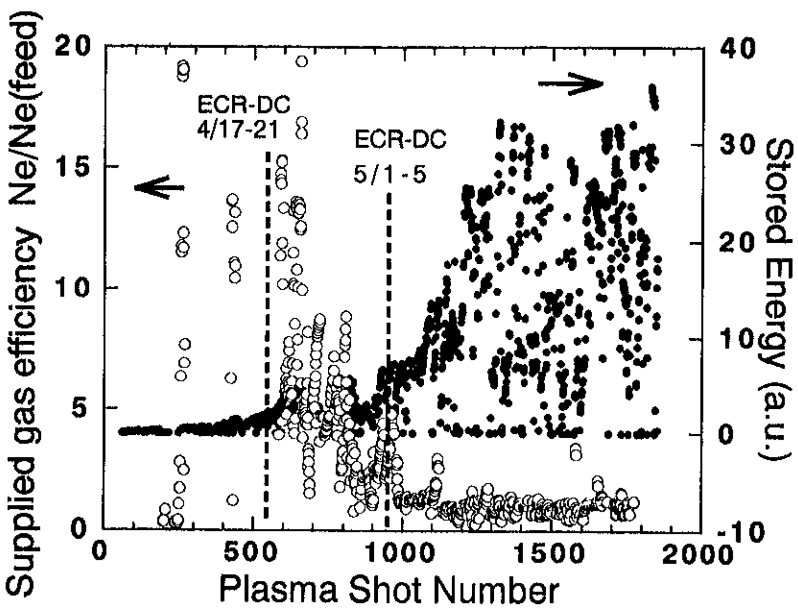

Fig.5 Improvement of gas efficiency and plasma stored energy with wall conditioning in LHD, where the gas efficiency defines the ratio of averaged plasma density to density supplied by gas-puffing.

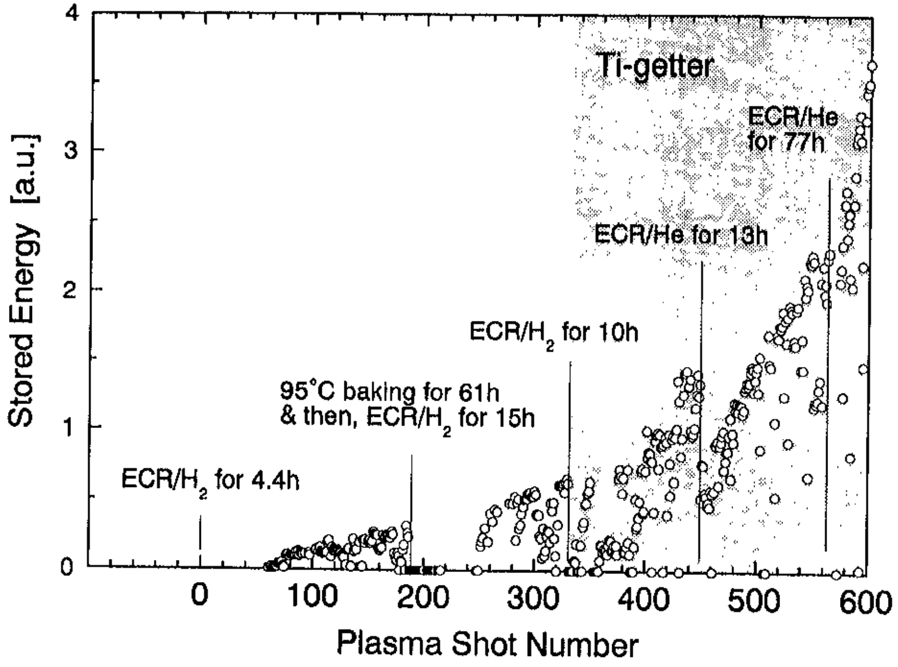

Fig.6 The effect of Ti-gettering on the plasma stored energy in the first campaign of LHD.

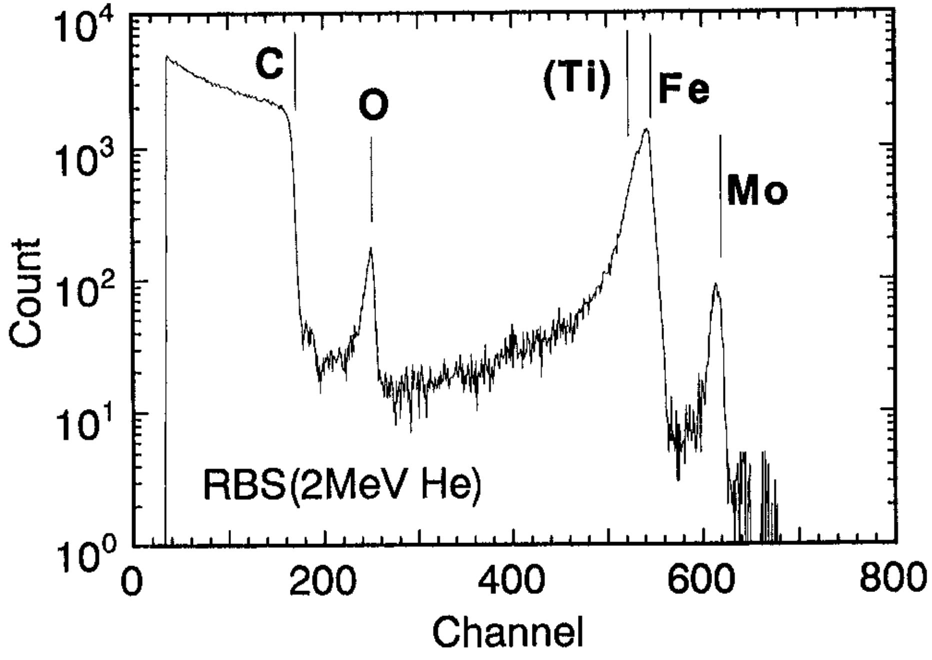

Fig.7 RBS spectrum of the graphite sample exposed to the divertor plasma in the first campaign of LHD.

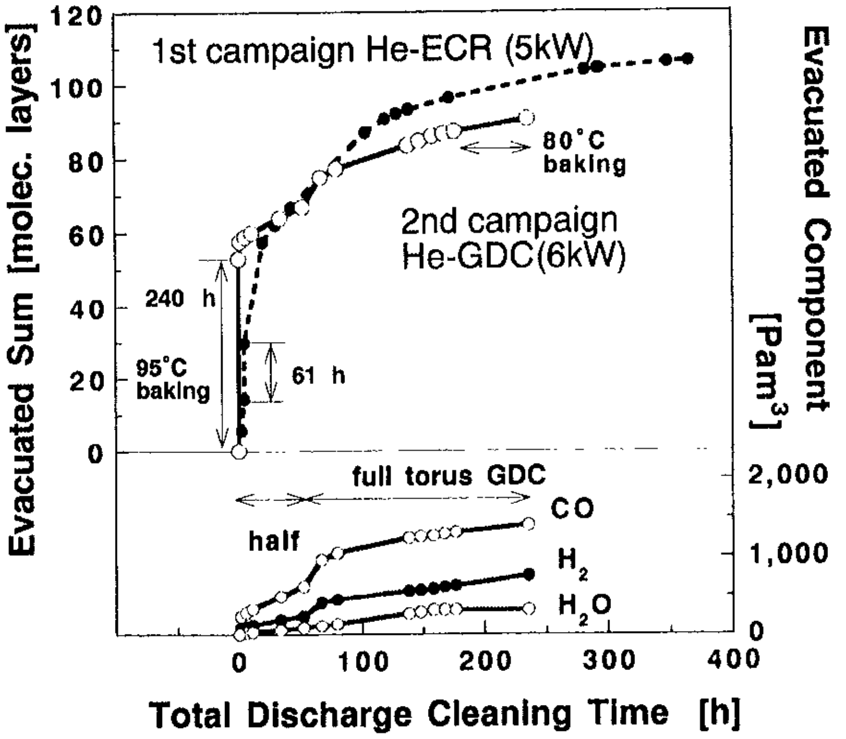

Fig.8 Gas evacuation under GDC in the second campaign in comparison to ECR in the first campaign of LHD.

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