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Particle balance on HT-7: Error analysis and first results

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Abstract

This paper introduces the utilization and first results of particle balance analysis on HT-7 deuterium retention study. Based on the present measuring system, at the end of a long pulse discharge, more than 90% of the puffed D_2 molecules remains inside the vacuum vessel. In the following dozens of seconds, about 30% of the puffed D_2 appears as outgassing and is extracted. The permanent D retention is at the level of 60%. More retention happens in longer pulse. Pumping speed is not a decisive factor for D_2 retention control.

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Keywords: Deuterium inventory; Gas injection and fueling; Particle balance; Retention

1. Introduction

Tritium retention is a critical issue for next generation long pulse tokamak, such as ITER. The device has to stop operating when the retained tritium reaches the safety threshold. In addition, the retained particle would influence the reaction efficiency and recycling. This issue has to be considered carefully when selecting the plasma facing material (PFM), and exploring the wall conditioning techniques. Consequently, evaluation of the fuelling particle retention is essential. Since its early application on TFTR [1], particle balance (PB) has been used in many tokamak devices, to name a few, Tore Supra, JET, JT-60U [2–4]. Though PB could not give a detailed illustration on a localized position as what sample analysis does, it has its own advantage of being able to provide a quick evaluation of the whole vacuum vessel. Comparing with the 'post mortem' analysis, using particle balance requires less complicated instruments and could provide result more quickly.

HT-7 [5] is a superconducting limiter tokamak with a major radius of 1.22 m, and the minor radius of 0.27 m, and its maximum plasma pulse duration is about 5 min. The poloidal, toroidal, belt limiters and the protection boards for rf antenna use doped graphite with SiC coating as the PFM. The total area of the graphite tiles facing plasma is about 1.6 m^2. During the conditioning period before the plasma experiment stage, the tiles are baked to 150–200 °C before D_2 and He GDC. The main cleaning method during the plasma experiment stage is ion cyclotron resonance cleaning using D_2 or He. For long pulse discharges, active cooling is used. The tiles are bolted to the water-cooling heat

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sinks. Though the initial operational temperature of the tiles is mainly at room temperature, most tiles are heated to 300 °C (measured by thermal couplers mounted at the back of tiles) towards the end of the discharge; while the maximum temperature in some tiles could surpass 1000 °C. Working gas is deuterium on HT-7. Helium is used mainly for wall conditioning. Since vacuum measurement which is required by PB analysis is a relatively slow diagnostics (response time could be as long as 100 ms for some vacuum meters), long duration of HT-7 pulses provides good platform for the retention study by using this method.

In Section 2, the system is described, and the errors are analyzed. Section 3 gives first results on the pumping speed and plasma pulse duration dependences of the D_2 molecule retention. In Section 4, the inventory of H isotopes inside the HT-7 vacuum chamber is discussed.

2. Particle balance analysis and error analysis

Particle equation analysis uses the equation set (1):

$$\begin{aligned} Q_{\text{puff}} &= Q_{\text{extract}} + Q_{\text{retention}}, \\ Q_{\text{puff}} &= \Delta P_{\text{tank}} \cdot V_{\text{tank}}, \\ Q_{\text{extract}} &= \int P_{\text{vv}} \cdot S \, \mathrm{d}t, \end{aligned} \tag{1}$$

where Q_{puff} is the input gas quantity, which could be obtained by monitoring ΔP_{tank}, the pressure difference of a fueling tank between before and after the plasma discharge; V_{tank} is the tank volume; Q_{extract}, the extracted gas quantity, equals partial pressure of Deuterium gas at the pumping port (P_{vv}) times effective pumping speed for D_2 of the pumping station (S). The difference between Q_{puff} and Q_{extract} is $Q_{\text{retention}}$, total retained D_2 molecule number.

There are many uncertainties concerning the PB analysis. When fast changing, the pressure inside the vacuum chamber needs 200–300 ms to be uniform. Gauge needs calibration and has different conversion factor for different gases. The density feedback control should also be setup carefully, because otherwise, when density decreases towards the end of the discharge, more gas would be puffed into the chamber without plasma due to the feedback operation. In Table 1, main elements affecting the error bar of PB evaluation are listed.

Table 1
Factors affecting error bar of PB analysis

Elements	Errors	Comments
Gauge	Affect P_{tank}(7%), P_{VV}(15%), S(20%)	Main error source, hard to be reduced
V_{tank}	3%	Small
Gas type	Affect P_{VV}(10%), S(10%)	Need residual gas analysis
Pressure distribution	Affect P_{VV}(10–20%)	Could be reduced in long pulse discharges

By careful design and calibration, common error of Q_{puff} is at the level of 10%, and that of Q_{extract} 35%. For a typical 60% retention ratio, for normal long pulse discharges on HT-7, when the Q_{puff} is at the level of 300 Pa l, the Q_{extract} is 120 Pa l, the error is at the level of 40%. It is difficult to make the quantitative evaluation with a high accuracy.

Table 1 shows that the highest error source is the pressure measurement. Therefore, if it is omitted as a system error, error of this evaluation is mainly from pressure distribution and gas type, and could be lower than 20% for discharges longer than a few seconds.

3. Experiments

An Inficon® CMR271 Capacitance Diaphragm gauge is used to measure the pressure drop of a 2.3 l fuel tank. In each of the four different pumping ports on HT-7, there is an Inficon® PKR251 Penning gauge (ion gauge mode) monitoring the pressure evolution. The conversion factor for D_2 is assumed to be the same as that of H_2, which is 2.4. An SRS200® RGA200 is used to analyze the quadrupole mass spectrum (QMS) of the residual gas in the vacuum chamber. QMS measurement illustrates that for D_2 discharges, basically more than 95% of the residual gas are the H isotopes. By assuming that H_2, HD, D_2 have the same partial pressure sensitivity factor, the percentages of H_2 and D_2 in the residual gas could be obtained.

Fig. 1 shows the time evolution of the particle balance during a plasma discharge based on the present PB measuring system. It should be pointed out that evolution of the puffed D_2 molecule number is a couple of seconds slower than the reality due to the slow pressure stabilization caused by narrow tube connection (this will be improved in the near future). It could be observed obviously that less than 10% of the puffed gas be extracted from the

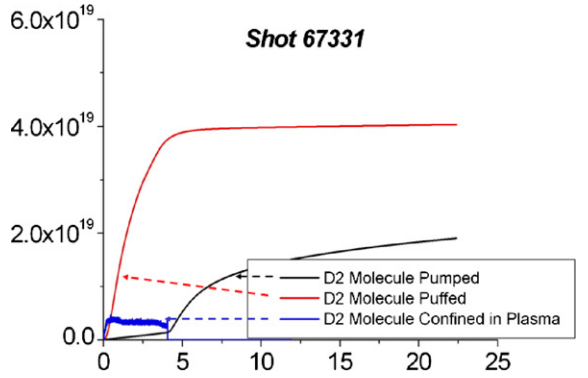

Fig. 1. Time evolution of the quantity of the puffed, the pumped and that confined in plasma D_2 molecule particle during a plasma discharge by PB analysis. The main points are the big retention until the end of the discharge (more than 90%) and a slow but obvious recovery of D_2 molecule from the vessel until about 20 s after the plasma termination.

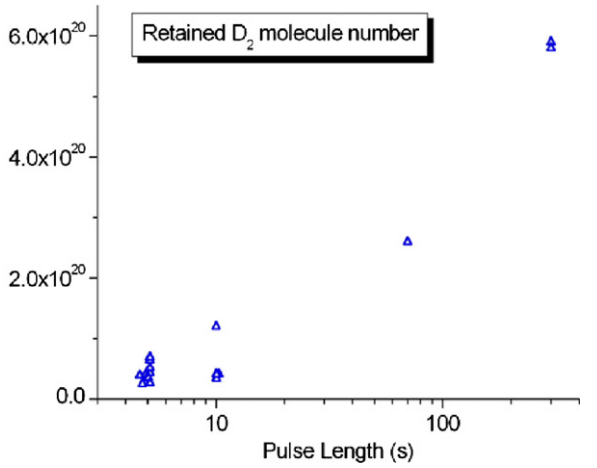

Fig. 2. Observation of pulse length dependence of the D_2 molecule retention level. The x-axis is logarithmic. The y-axis is the retained D_2 molecule number taking into account for the recovery after plasma termination.

vacuum chamber during the plasma discharge. Until dozens of seconds (this period changes according to the plasma duration, and usually longer for longer pulses) after the plasma termination, totally about 40% Q_{puff} has been pump out. The retained D_2 inside the chamber (in this paper, if not specially noted, this refers to the total puffed particles subtracting the pumped ones until dozens of seconds after the end of one discharge) is about 60% of the totally puffed D_2 particles.

Evaluation of the retention in the form of percentage may not be a good idea on HT-7. Take a 5 s discharge, pulse number 78467, as one example. $Q_{puff} = 342$ Pa l. $Q_{extract} = 110$ Pa l. The D retention ratio is $68\% \pm 16\%$. Such a big error bar almost covers the whole range of retention result calculated in HT-7. Absolute D_2 molecule number is used for the following experiments.

A series of plasma discharges with similar parameters (electron density, plasma current, no major disruptions) were compared to study the pulse duration dependence of retention. As is shown in Fig. 2, though it would be seen that longer pulse tends to cause higher retention quantity, the evolution of the retained D_2 molecule number versus plasma duration shows a relationship less than linearity. Considering the observation that the temperature of a few tiles keeps on increasing throughout the discharge, especially for the minute-scale pulses, this factor might be a key factor for an implied tendency towards saturation. More data will be collected in the future to verify this.

Retained molecule number for discharges with different pumping speed is also compared among a few 5–10 s pulses of similar plasma current and electron density. In Fig. 3, the pumping speed ranges from a couple of hundred of liters per second to a couple of thousand, It could be seen that though the speed varies by ten times, retained D_2 molecule number of most pulses is kept within the similar level. No clear pumping speed dependence of retention could be observed. Though PB shows different

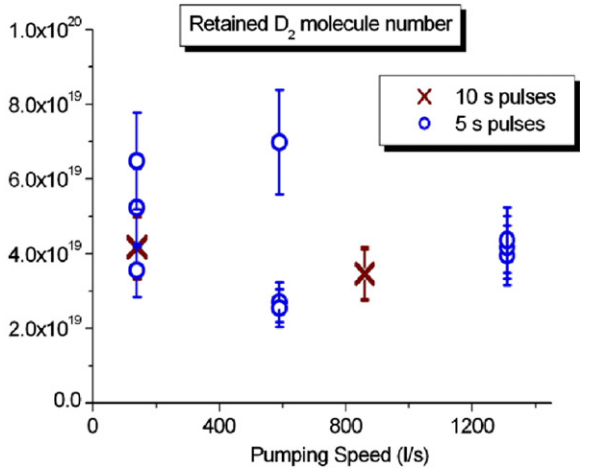

Fig. 3. Observation of pumping speed dependence of the D_2 molecule retention level for 5 s and 10 s discharges. The pumping speed ranges from 100 to 1300 l/s. The y-axis is the retained D_2 molecule number taking into account for the recovery after plasma termination.

retention for pulses at 0.6 m^3/s (physics behind is not understood), it could be concluded that the pumping speed is not a decisive factor for retention.

4. Discussion

The pressure inside the vacuum chamber after the plasma termination shows different evolution from that without plasma breakdown. Though there is no gas puffing during that period, pressure has a big jump from 10^{-4} Pa to 10^{-3} Pa, even 10^{-2} Pa, and keeps rising for a few seconds for minute scale plasma discharges. The evolution of partial pressure evolution of a plasma discharge measured by QMS is shown in Fig. 4. The sampling speed of the QMS is at the level of 100 ms, thus the quick change corresponding to the breakdown could not be shown. However, the pressure evolution corresponding to the termination of the discharge and the afterward period is very clear. There is a big rise of the vessel pressure and a slow (comparing with the pumping time constant of the system) decay period following that. QMS also shows that there are large quantity of hydrogen in the residual gas (especially could be higher than 50%, even as high as 80% shortly after boronization), coinciding with the observation of high H/(H+D) ratio in plasma by spectroscopy diagnostic. H/H_2 is observed clearly in He fueled discharges as well.

The source of the hydrogen is an open question so far. One source could be the boronization material, $C_2H_{12}B_{10}$ [6]. An important proof is that both the H/D ratio and the percentage of H_2 within the residual gas increased after boronization. Samples have been installed inside the vacuum chamber. The eroded and deposited ones will be analyzed in the near future to check the capacity of retaining H isotopes.

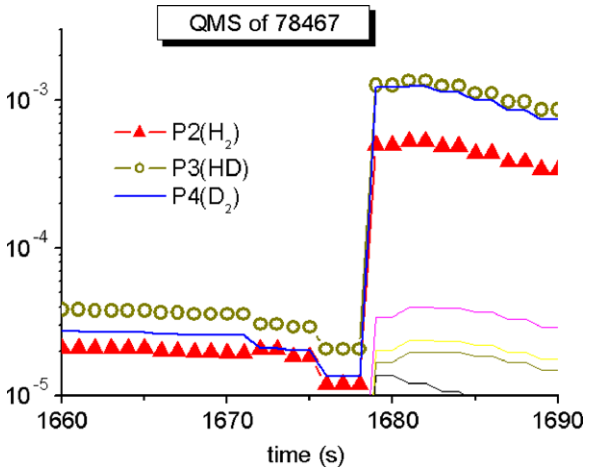

Fig. 4. Partial pressure evolution for a plasma discharge. The discharge starts at about 1670 s and terminates at about 1680 s. P2, P3, P4 correspond to H_2, HD and D_2, respectively.

Because of the low particle exhaust ability of HT-7, up to 90% input gas is retained until the end of the discharge. From the end of the discharge to dozens of seconds afterwards about 30% input gas could be released and extracted from the chamber. The structure of the tile might explain the behavior of D inventory. HT-7 limiter tiles are made of doped graphite covered by thick SiC coating with crystal structure. After exposure to plasma for a certain period, it is observed that in the eroded area the coating is removed and more likely replaced by a lamellar structure; while the deposited area is likely to be covered by C layer [7]. Under this condition, during the discharge large quantity of D_2 is trapped on the enlarged surface area. At the same time, due to the plasma surface interaction, the temperature of some tiles would keep on rising until the end of the discharge and remain for a few seconds and drop gradually. This might be the reason for the outgassing and pressure evolution. Post mortem analysis will be carried out to evaluate the retention properties of the tiles.

5. Conclusion

Particle balance is used to evaluate D retention during long pulse discharge on HT-7. Basically more than 90% of the input D_2 molecules are retained at the end of the discharges. Taking into the account of the recovered D_2 until dozens of seconds after plasma termination, generally speaking, about 60 % of the puffed gas is retained relatively permanently (on the level of an experimental day). More retention happens in longer pulse. Pumping speed is not a decisive factor for D_2 retention control.

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