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Hydrogen Recycling and Wall Equilibration in Long-Pulse Operation

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Abstract

Wall recycling of hydrogen isotopes effects fueling and plasma performance. In most present fusion devices with pulse lengths in the range of several seconds, recycling evolves during the discharge and, hence, fueling conditions are not stationary. In order to find out what is needed to provide stationary recycling conditions, this paper studies the particle balance between plasma, wall, and external exhaust. A crucial factor is the recycling coefficient which, on a given surface, depends on the particle flux and trapped fluence. For a typical fusion device, the particle flux to the wall surface can vary over four orders of magnitude and the recycling coefficient will change accordingly. As an example, we have studied the wall surface of the DIII-D tokamak and calculated the incident particle fluxes with the DEGAS code for 85 segments of the wall. For each of these segments we have calculated the trapped fluence and recycling coefficients for a typical discharge. The result shows that different parts of the vacuum vessel are important during different phases of the discharge.

Keywords:

recycling, particle balance, trapping, wall pumping, wall equilibration

1. Introduction

Wall recycling of hydrogen isotopes affects wall inventory and plasma performance. Wall recycling usually evolves as a function of time during the discharge from low recycling (depleted walls) to high recycling (saturated walls). Due to the increasing recycling coefficient, plasma fueling and plasma performance can potentially change as a function of time. In order to shed some light on the processes involved in recycling and wall equilibration, this paper investigates wall recycling processes by analyzing space- and time-dependent recycling coefficients.

2. Particle Balance Between Plasma, Wall, and External Exhaust

Of the total amount of gas puffed into a tokamak or stellarator plasma discharge, typically only 10–20% ends up in the plasma itself, whereas the rest is implanted into the walls. If the device is equipped with external particle pumping, a certain fraction of the total gas can also be exhausted from the system. To obtain a better understanding of the distributions of the total gas, we construct a particle balance including the plasma inventory, wall inventory, and the exhausted gas. In the following equations, N_{pl}, N_w, and N_{pmp} are the inventories of the plasma, the wall, and the pump respectively:

$$\frac{\mathrm{d}N_{pl}}{\mathrm{d}t} = \eta \cdot \Phi(t) - \frac{N_{pl}}{\tau_p} + (1-\varepsilon) \cdot R \cdot \left[\left(1-\eta\right) \cdot \Phi(t) + \frac{N_{pl}}{\tau_p} \right] + (1-\varepsilon) \cdot \alpha \cdot N_w \cdot \left[\left(1-\eta\right) \cdot \Phi(t) + \frac{N_{pl}}{\tau_p} \right] \quad (1)$$

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$$\frac{\mathrm{d}N_w}{\mathrm{d}t} = (1-R)\cdot\left[\left(1-\eta\right)\cdot\Phi(t)+\frac{N_{pl}}{\tau_p}\right] - -\alpha\cdot N_w\cdot\left[\left(1-\eta\right)\cdot\Phi(t)+\frac{N_{pl}}{\tau_p}\right] \qquad (2)$$

$$\frac{\mathrm{d}N_{pmp}}{\mathrm{d}t} = \varepsilon\cdot R\cdot\left[\left(1-\eta\right)\cdot\Phi(t)+\frac{N_{pl}}{\tau_p}\right] + +\varepsilon\cdot\alpha\cdot N_w\cdot\left[\left(1-\eta\right)\cdot\Phi(t)+\frac{N_{pl}}{\tau_p}\right] \qquad (3)$$

Here η is the fueling efficiency, ϕ is the gas input (TorrL/s), τ_p is the particle confinement time, R is the recycling coefficient, ε is the fraction of the gas flow exhausted by the divertor or pump limiter, and α is the particle-induced desorption (PID) coefficient. The gas input ϕ is taken as a step function between $t = 0$ and $t = 5$ s, and the particle balance as a function of time is obtained by integrating Eqs. (1) to (3) numerically. The result is depicted in Fig. 1 for a fixed recycling coefficient of $R = 0.85$. It can be seen that at a pulse length of $t = 5$ s the density is not stationary. The particle confinement time is taken as $\tau_p = 0.2$ s, so that the global confinement time with the given $R = 0.85$ is $\tau_p^* = \tau_p/(1 - R) = 1.3$ s. If, on the other hand, pumping is turned on, as indicated in Fig. 2, τ_p^* is 0.5 s and the density is stationary, i.e. if the pulse length is large compared to τ_p^*, the balance between plasma density, wall pumping, and external exhaust is stationary. This can also be achieved with a lower recycling coefficient, since it reduces τ_p^*, and the critical parameter is the ratio of the pulse length to τ_p^*.

While this example demonstrates the effect of the various elements of the balance equations, in reality the recycling coefficient is not constant and will change as a function of time during the discharge. In the next paragraph we will develop a simple analytical formula that can be used to describe the time-dependence of the recycling coefficient in the above balance equations.

3. Fluence-Dependent Recycling Coefficient

During a plasma discharge the local recycling coefficients evolve as functions of the trapped fluence which is usually a function of time. So, for a given incident flux, the recycling coefficients evolve as a function of time. We have constructed an analytical formula for the recycling coefficient which is a good approximation of measured values [1] and also of TRIM calculations published by W. Eckstein [2]. The recycling coefficient as a function of the trapped particle density

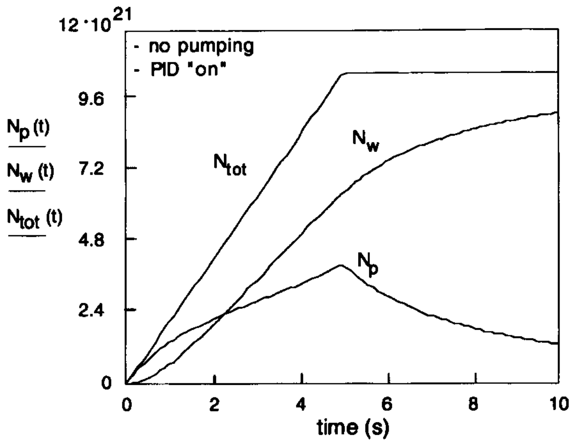

Fig. 1 Particle balance with $\tau_p^* = 1.3$ sec, including PID and no external pumping.

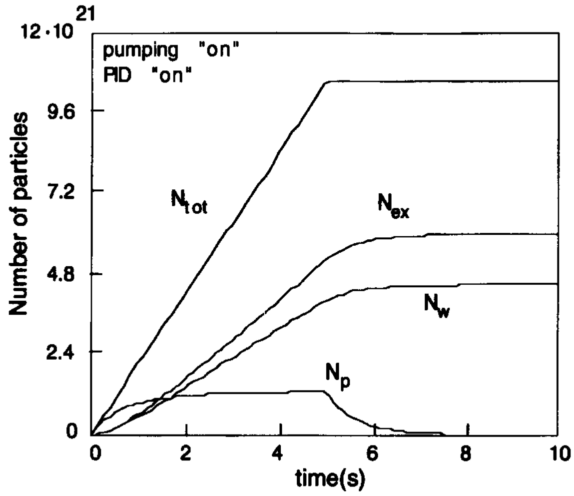

Fig. 2 Particle balance with pumping turned on and $\tau_p^* = 0.5$ sec

n_{tr} is:

$$R(n_{tr}) = a\cdot\tanh\left(\frac{n_{tr}-n_{sym}}{\delta}\right)+c. \qquad (4)$$

The parameters a and c adjust the initial value and the final value of R (unity), n_{sym} and δ are used to adjust for the incident particle energy. For particle energies of 50, 100, 200 eV, the recycling coefficient according to Eq. (4) is shown in Fig. 3. The number of trapped particles resulting from this recycling coefficient as a function of incident fluence is depicted in Fig. 4.

It is obvious that different parts of the vacuum vessel will behave differently with respect to recycling. If we introduce the fluence-dependent recycling into the

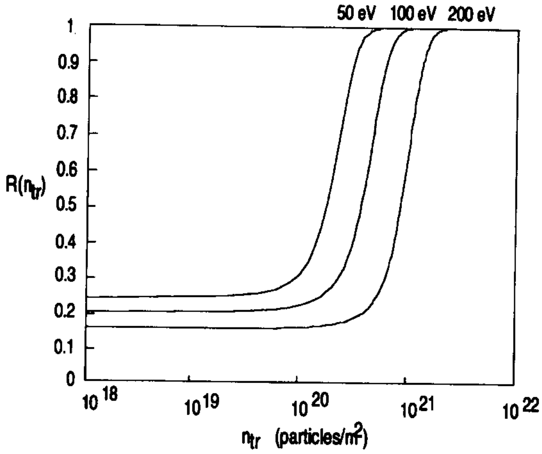

Fig. 3 The recycling coefficient as a function of trapped particle fluence.

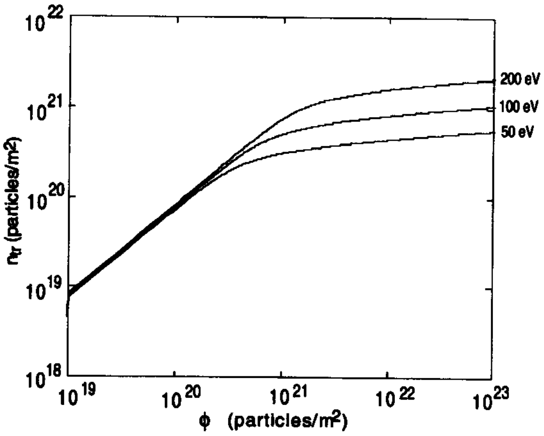

Fig. 4 Trapped particle fluence n_{tr} as a function of incident fluence and particle energy.

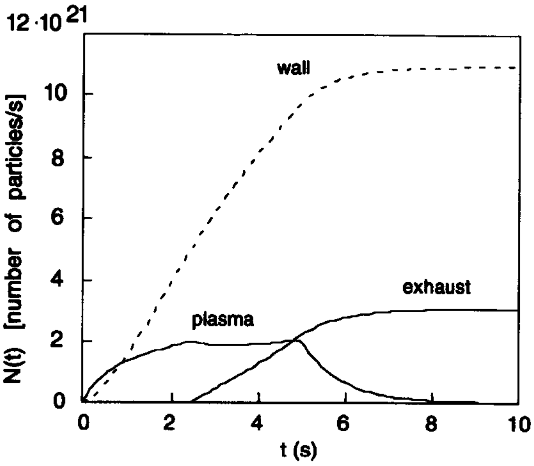

Fig. 5 Density evolution with fluence-dependent recycling coefficient and external pumping.

balance equations , we get the density evolution with a variable recycling coefficient. The resulting particle balance with external pumping is shown in Fig. 5, where pumping is switched on at $t = 2.5$ seconds.

4. Spatial Variation of Recycling Coefficient

Having a model for the fluence- or time-dependence of the recycling coefficient is not sufficient to describe recycling in a fusion device, because the particle fluxes incident on different parts of the wall vary widely, leading to different evolutions of the recycling coefficient on different parts of the wall. To complete the picture, we investigate the spatial dependence of the recycling coefficient using a concrete example, the DIII-D vacuum vessel.

For these calculations the wall was subdivided into 85 poloidal segments for which the incident particle flux was determined with the DEGAS code [L.W. Owen]. The evolution of the recycling coefficients in each of the segments was determined with Eq. (4). The division of the vacuum vessel wall into zones is indicated in Fig. 6 and the recycling coefficients of 6 wall segments are depicted in Fig. 7.

In Fig. 7 the recycling coefficient as a function of time remains low in segment 1, approximately at the inner midplane where the flux is low. The three highest

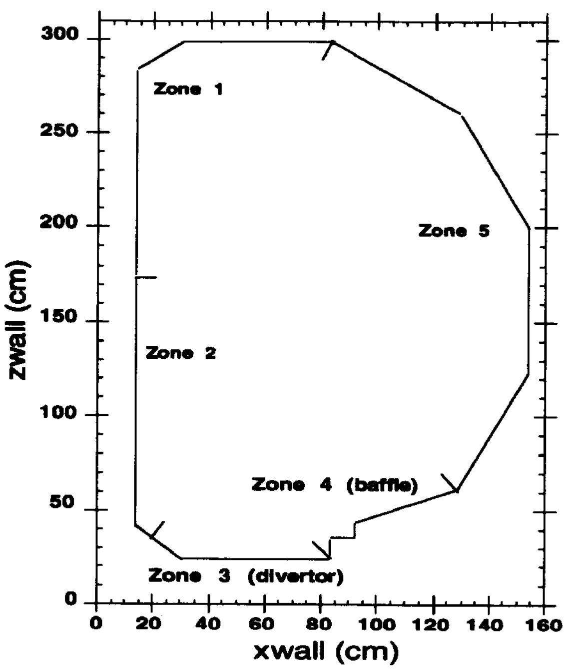

Fig. 6 The (5) zones of the DIII-D vacuum vessel.

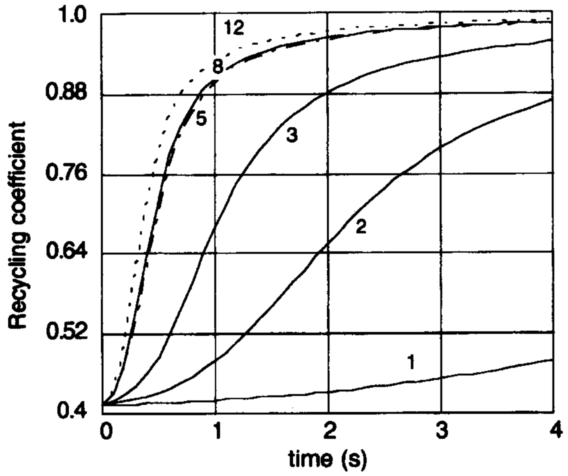

Fig. 7 Recycling coefficients as a function of time on 6 segments of Zone 2.

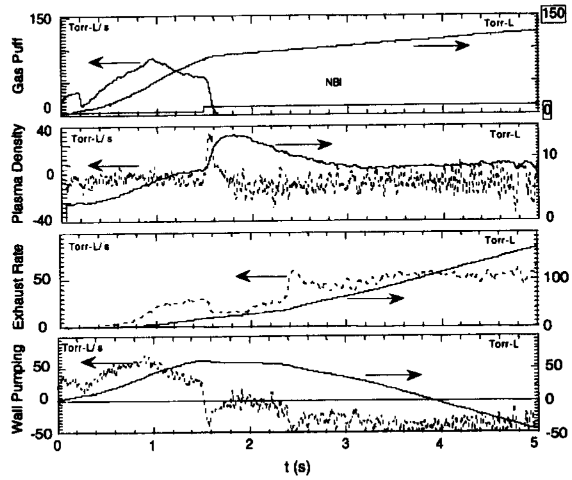

Fig. 9 Particle balance in a DIII-D discharge: input gas puff, plasma particle content, divertor exhaust, and wall inventory.

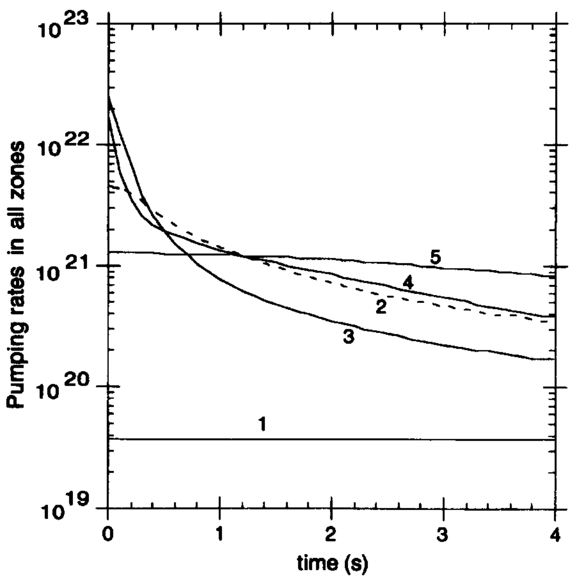

Fig. 8 Pumped particle fluxes in Zone 1 through 5 (1 = top wall, 2 = inner wall, 3 = divertor, 4 = baffle, 5 = outer wall).

recycling coefficients correspond to the segments of high fluxes close to the inner strike-point. Combining all segments into 5 zones and adding up the fluxes for all segments in each zone, we obtain the pumped particle flux in each zone. The pumped particle fluxes for a given time and for each segment are depicted in Fig. 8.

The initial pumping is dominated by the divertor (Zone 3) due to the large surface area and high flux. After about 0.2 s the total flux pumped by the inner wall surpasses the flux pumped in the baffle. Then, after about 1 second, the neutral flux on the baffle becomes equal to the flux on the inner wall, and at the same time the overall pumping becomes dominated by the outer wall. Although the outer wall flux is small, the recycling coefficient is low and the surface area is large and, therefore, the total pumping here dominates the global recycling.

Using the recycling coefficient in Fig. 3 for 100 eV particles; a trapped fluence of 10^{21} m^{-2} would lead to recycling near unity with the surface near equilibration. In the divertor, incident fluxes in excess of 5×10^{22} $m^{-2}s^{-1}$ have been observed. This means that a trapped fluence of 10^{21} m^{-2} could be reached within one second, whereas other areas, with particle fluxes of e.g. 10^{20} $m^{-2}s^{-1}$, would need several hundred seconds to reach the saturation fluence. Fortunately, this situation can be controlled by applying external pumping. As indicated above, an additional particle sink, as introduced by external pumping, can dominate the overall recycling and shorten the equilibration time correspondingly.

5. Dynamic Retention and External Control

It has been shown that the change of the wall inventory during a plasma discharge can be controlled in either direction, i.e. it can be either increased or decreased. Without external pumping, the inventory will eventually have to increase until the walls are saturated. However, when external pumping is applied, the wall inventory can be depleted and the particles removed from the walls are eventually removed from the system.

This leads to a totally different picture of wall equilibration. In a plasma discharge with external pumping, the walls respond to externally imposed sources and sinks. The wall inventory becomes dynamic. As a consequence, the recycling coefficient and, therefore, the wall equilibration time can be controlled externally.

This depletion of the wall inventory has been demonstrated in several tokamaks such as Tore Supra, DIII-D, and TEXTOR. As an example, we show in fig. 9 the evolution of a DIII-D discharge with gas puff, plasma inventory, particle exhaust, and wall inventory [3]. The wall inventory is usually obtained from the particle balance.

The left-hand-side of the plots depicts the particle rates in TorrL/s and the right-hand side shows the particle inventories in TorrL. The figure shows that, with sufficient pumping, the external gas source can be balanced and the exhausted gas can surpass the input. For constant plasma density, the extra particles can only originate from the walls. Similar results have been reported from other machines [4].

6. Summary and Conclusion

Wall equilibration due to recycling can take hundreds or even thousands of seconds if no external particle exhaust is provided. However, providing an external particle sink to the particle balance, can force the equilibration to shorter times. In addition, it has been demonstrated that the wall inventory can be dynamically changed with external exhaust such as provided by pumped limiters or divertors, so that the recycling coefficient becomes one of the controllable parameters in a magnetic fusion device.

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