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ABSTRACT

Particle retention is a major constraint for future fusion devices like ITER in which the amount of tritium will be strictly limited for safety reasons. In the EU Task Force on plasma wall interaction, efforts are underway to investigate the gas balance, the particle retention and removal in fusion devices. Gas balance in JET, ASDEX Upgrade, TEXTOR and Tore Supra are reported in this paper. In all these devices, a peak in the wall loading is observed, at the beginning of the plasma, which is attributed to the saturation of the area in contact with the plasma. These particles are always recovered at the end of the plasma (dynamic retention) while for longer plasma operation, the particle retention can become proportional to the discharge duration. The effects on the particle retention by different fuelling methods, gas puffing, pellet injection and Neutral Beam Injection (NBI) are reported,there is only a very weak reduction in particle retention with pellets compared to gas injection, while with NBI a transient wall depletion is always observed but accompanied by a density drop which requires additional gas puffing to recover the target plasma density. For all the devices, the recycling flux dominates the particle fluxes and neither pumping nor fuelling allows to modify/control the recycling flux and consequently the retention flux. The particle recovery between pulses by gas release is always similar in the absence of disruptions. However, for longer plasma durations this contribution becomes negligible in the overall balance. Finally, conditioning methods (glow discharges) and discharges cleaning show a particle recovery which is independent of the particle retention in the previous plasma operations.

1. INTRODUCTION

The evaluation of the hydrogenic retention in present tokamaks is of crucial importance for the long discharges foreseen in ITER [1]. Investigation of gas balances, particle retention and removal in fusion devices is a major task of the EU task Force in plasma wall interaction. This paper presents a comparison of the gas balance in JET, ASDEX Upgrade, TEXTOR and Tore Supra, which operate under different magnetic configurations, plasma edge conditions and plasma facing temperatures. In ITER, the first wall area will be covered with Be (700m^2) and W (100m^2) on the upper baffle and dome. The carbon will be restricted to the strike points in the lower divertor, but in spite of the relative small area (50m^2, it represents a huge potential reservoir for tritium retention and hydro-carbon formation. The first part of this paper reports on particle balances in different carbon tokamaks. The second part compares the resulting particle retention with different methods of fuelling, such as gas, pellet and neutral beam fueling (NBI). The third section deals with reports on the particle recovery after the discharges, including the effect of wall conditioning. Finally, the different method to control and/or limit the particle retention are discussed.

2. PARTICLE BALANCE DURING PLASMA OPERATIONS

For a constant density throughout the discharge, two phases can be distinguished in the particle balance. At the beginning of the shot, a peak in the wall loading is observed, attributed to the saturation (D/C ~ 0.4) of the surface area in contact with the plasma. This area saturates quickly, within τ ~1-2 sec in

JET and ASDEX Upgrade divertor region while it is somewhat longer in TEXTOR or Tore Supra (τ~10-15sec) due to the different particle energies. Figure 1 shows the typical time evolutions of particle fluxes for a typical L mode JET discharge. (I_p = 2MA, B_T= 2.4T, $<n_e>$ = $3.8\times10^{19}m^{-3}$ and 3MW of ICRH) [2]. The retention phases can be distinguished from 55 to 57 and from 57 to 66 sec. For the devices discussed here, the areas in direct contact with the plasma are between 0.5 to $3m^2$ and edge energy ranges between 10 to 50eV, corresponding to a maximum reservoir of about 2-5 $\times10^{21}$ D for a saturation with D/C ~ 0.4. This reservoir is low compared to the retention observed at the beginning of the pulse particularly for low T_e plasmas, suggesting that the direct implantation is not the dominant retention process. The second phase has a longer time constant which can be attributed to co-deposition and Charge eXchange (CX) flux retained in areas far away from the plasma. However, for all machines, the wall loading can be negative or positive during this phase depending on the level of gas injection. This can be seen e.g. in fig.1, where the weak decrease of the wall loading results from the drop on the gas puff and the plasma density.

It is worth noting that the long term retention is not influenced by previous plasma operations. Indeed, series of very long discharges (particularly for 3 consecutive discharges cumulating 15 min 6 sec of plasma in less than 2 hours, in a retention of ~6 $\times10^{23}$D, compared to the typical 10^{20} D of the plasma content) show no evolution in the particle balance. This is shown in figure 2. For the three discharges (without any conditioning between) the gas injection is always about twice the particle exhaust. Two phases are observed for the temporal behaviour of the wall retention rate (Ret = (Injection-Pumping)/Injection). In the first phase (up to 100s), the retention decreases from 4 $\times10^{20}$ D s^{-1} to 2 10^{20} D s^{-1}, and remains constant in the second phase, with a typical value of 2 $\times10^{20}$ D s^{-1}. Even after 15 minutes of cumulated plasma operation, no sign of wall saturation is observed but the wall inventory increases proportional to the plasma duration. In TEXTOR, plasmas are much shorter (the order of 10 sec) and the particle balance is dominated by dynamic retention, explaining that a large fraction of the retained hydrogen is released from the walls after the discharge [3]. Also in ASDEX Upgrade, JET, TEXTOR and Tore Supra, the total retention exceeds also largely, by more than a factor of 10, the saturation reservoir of 0.4D/C, of the area in contact with the plasma. This suggests that additional reservoirs (porosity of the CFC) can play a role in this transient retention [4].

In JET, for a repetitive series of L mode shots (39 similar pulses – Vessel temperature of 200˚C – see fig.1) always the same amount of deuterium is retained and then released between the pulses. This quantity is very reproducible and about 3×10^{22}D exceeding about 10 times the saturation capabilities of the area of ~$3m^2$ in direct interaction with the plasma. All the gas retained during the plasma is recovered between these pulses, suggesting that codeposition is not effective and the retained gas has not penetrated deeply in the material.

The analysis of the gas balance over a series of long discharges in Tore Supra is shown on figure 3. The figure shows the cumulative gas balances during long discharges permitting the separation between the dynamic and long term retention. This yield the long-term retention for a wall temperature of ~400K. The amount of particle released between discharges is the same within a factor of ~2, independently of the plasma duration and the absolute amount of retention. Thus, the contribution of the particle release between discharges becomes negligible in the overall gas balance. The particle retention derived by this method in Tore Supra is much larger when compared e.g. with that derived from post mortem analysis, in TEXTOR [5]. This could be the result of the higher operating temperature (320^{o}C for the liner) leading to lower retention in the co-deposited layers. Since the fuelling rate of the Tore Supra shots is low (recycling near 1 and low external pumping), the fraction of retained fuel becomes high (50%). TEXTOR, has large fueling in general leading larger outgasing in between shots and thus a smaller fraction of retention. However also the absolute retention in TEXTOR is lower compared to Tore Supra. [3]

In ASDEX Upgrade, with 15% of W coating (Tvessel ~20^{o}C) and with the DIV IIB divertor, the retention is about 30% during the pulses, for gas fuelling rates higher than 10^{22}Ds^{-1} but also dominated by the dynamic retention. [6]. On figure 4 the ratio of the total gas recovered (D pump out) to the gas input is displayed. It can be seen that at low plasma density (low gas injection) the ratio exceeds 100% which indicating that the wall inventory is reduced at low plasma densities. However, for medium injection (>3×10^{22}D), this ratio is below 100% indicating wall loading for these short pulses.

Recent long discharge experiments (>30sec) in JT-60U show that a saturation occur after few discharges [7] that the history of the gas balance affects the plasma characteristics and the wall tends to saturate by repeating pulses. In spite of the higher vessel temperature of ~420K, this behaviour could be linked to the high surface temperatures reached during plasma operation on the inner and outer targets. Since there is no active cooling the carbon bulk temperature increases during the discharge and also from pulse to pulse leading to a non negligible outgassing. This is consistent with the low D/C ratio of about 0.02 observed in the carbon layers [8]. This may also contribute to the lower retention observed in JET with the MKII-GB SRP [2] compared to the 40% of T retention obtained during the DTE1 experiments with the MKIIA divertor [9]. A newly installed Quartz microbalance detector on the inner louver entrance [10] show that deposition increases when the strike point is moved along the vertical target towards the pump duct entrance and even more strongly when the strike zone is moved onto the horizontal target. This was the case in the MKIIA campaign and likely the origin of the large deposition on the louver maintained at ~50^{o}C during this campaign. On areas in direct contact with the plasma, tritium can be removed by isotope exchange during deuterium plasma operation, but this method has a limited efficiency. [11].

3. FUELLING METHODS

In Tore Supra, discharges of 2min fuelled by gas and by pellet (low field side) have been compared. [12], shown in figure 4. and particle balances have been performed for both discharges. (I_p = 0.6MA, $<n_e>$ = 1.5×10^{19}m^{-3}). The low fuelling efficiency of the gas injection is suspected to be one of the reasons leading to high retention for the gas fuelled long discharges [13].

Figure 5 displays the particle balances for the two discharges for the “most” steady state part, from 25 to 90 sec for the gas fuelled from 25 to 115sec for the pellet fueled discharge respectively. As can be seen the total quantity of particles required to maintain the plasma density is comparable and the exhausted particle flux by the active pumping of the TPL are also similar. Since the plasma parameters are very close, this shows that the retained flux is correlated to the recycling flux. Figure 5 shows the retention as a function of time for these two discharges. It can be seen that the difference between the two fuelling methods is rather weak. With a retention of 59 and 49% for the gas and pellet injection respectively. This modest difference is suspected to be the result of the LFS pellet fuelling efficiency associated to LHCD. Indeed, even with the delay imposed in the LH power (notching), for these experiments the suprathermal electrons were still present. This could explain the low difference between the gas and the pellet shots in comparison to the two previously described long discharges (see fig.5).

In JET, experiments with neutral beam fuelling for 5 sec during the DTE1 campaigns show (fig.6) that during the NBI fuelling phase (12 - 18 sec) (T: ~ $6.15\times10^{20}s^{-1}$) the T wall inventory decreases abruptly (red plot) as soon as the power is applied while it recovers close to the equilibrium. However, this transient effect is accompanied with a decrease of plasma density which requires additional particle fueling to keep and/or to attain the target density.

In JET, new attempts have been made for a particle balance in hydrogen/deuterium operation. The experiments with calibrated pumping speed allowed a precise gas balance over a full day of operation [2]. The particle retention during the plasma was lower than previously observed [14]. This behavior is in contrast with the DTE1 experiments showing a tritium retention of 40% [9] over the full day of experiments and of the order of 60% during the plasma operation [11].

A possible reason for this is that the codeposited layers are formed on the inner vertical targets in the MKII-GB SRP and are exposed to high power flux reducing the D/C ratio while layers with high D/C ratios are formed on the louver area in MKIIA divertor. This is supported by the QMB results [9] showing a high C depositon rate with the strike points on the horizontal divertor plate. This could be correlated to the higher tritium retention observed during the DTE1 campaign. [10]. Depending on the location of the strike points, the effects of the ELMs on the C deposition rate and the associated D retention can be largely different. With the strike points on the horizontal target the effect of the ELMs on the carbon deposition in the QMB area is not measurable. This could also explain the difference of the JET compared with JT60U showing a low particle retention. [8].

4. PARTICLE RECOVERY BY GLOW AND DISCHARGE CLEANING

In ASDEX Upgrade, the Helium Glow Discharges (HGD) applied between pluses allows pulses to recover a main part of the retention which can be very high for the strongest gas injection (up to 40% for total input of 10^{23}D). It is worth noting that the amount of particles recovered by the conditioning procedure is always about the same, i.e. 8×10^{21}D as shown on figure 7. suggesting that the same areas are depleted with the HGD independently from the retention observed during the pulse. The same behaviour is observed in Tore Supra where the HGD recover also always the same amount of particles independently of the total particle retained during the previous experiments [4] even for the long discharges with high retention. In ASDEX Upgrade, about 60% of the retained particles are recovered between pulses, while 10-20% are recovered over a characteristic time of a day. The resulting long term retention is about 10-20%. These values are consistent with the averaged fuel retention rates from particle balance of various JET divertor campaigns of 3-10% [14] and with a value of 8-10% in TEXTOR obtained from post mortem tile analysis. In the long discharges in Tore Supra a steady increase of the long term vessel inventory with a rate of about $2\times10^{20}Ds^{-1}$ is seen. This value is about ten times the fuel retention rate evaluated in TEXTOR from post mortem surface analysis and integrated fuel input, and compares with averaged fuel retention rates between about 1.5 and $5\times10^{20}Ds^{-1}$ estimated from JET.

During the “pure” D plasmas just after the T phase at JET, a larger D retention is initially observed which then gradually returns a lower value on successive pulses. This is indicates that the global particle retention (D + T) does not change and that the amount of T removed from pulse to pulse decreases after ~10 pulses as the isotopic ratio in the films decreases. The excess of D retention is attributed to isotopic exchange with the tritium that was previously implanted in the wall (the D replaces the T). With total carbon area in JET of ~200 m^2 this would correspond to a maximum retained fluence of $\sim10^{21}m^{-2}$ which is consistent with implantation of deuterium with an incident energy of 200eV before acceleration in the sheath. However, the amount of T removed by isotopic exchange has been found to be limited to about 2×10^{23} T compared with the 10^{24}T trapped at the end of the first phase of the DTE1 campaign [11].

CONCLUSIONS

Analysis of fuel retention in real time in the early non activated phase of ITER operation will be necessary to quantify and qualify the future plasma scenario in DT operations. The overview presented in this paper shows that for short pulses (5 to 15sec) performed in the majority of the present fusion devices, the gas balance is dominated by the dynamic retention and that the majority of the particles retained during the plasma is recovered at the end of the pulse. The fuelling method by gas, pellets and NBI do not modify significantly the retention. A similar global behaviour of the fuel retention is seen in ASDEX Upgrade, JET, TEXTOR and Tore Supra independently of the machine. However, for long discharges (>2-3 min) the retention is very likely dominated by co deposition in areas which do not affect the plasma characteristics of the following discharges. Higher wall temperatures reduce the D retention, by formation of layers with a lower D/C ratio (~0.05 in JT-60U) while the effect of plasma geometry in the divertor appears to modify significantly the C deposition rate, in particular also under conditions of large ELMs.

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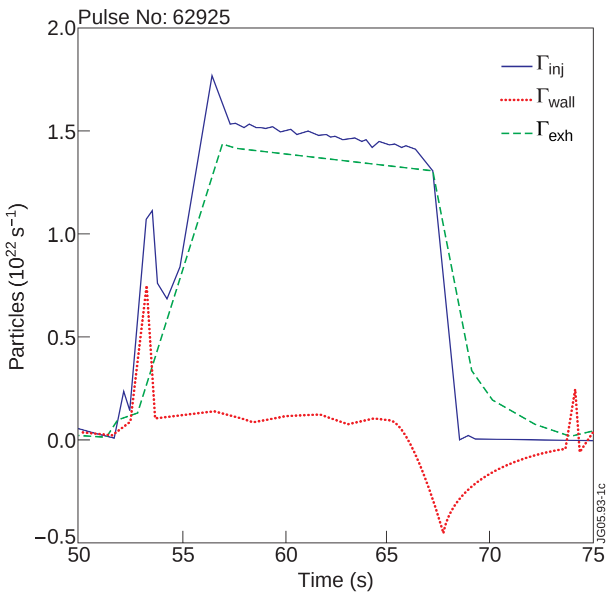

Figure 1: Time evolution of typical particle fluxes during L mode plasma JET [2].

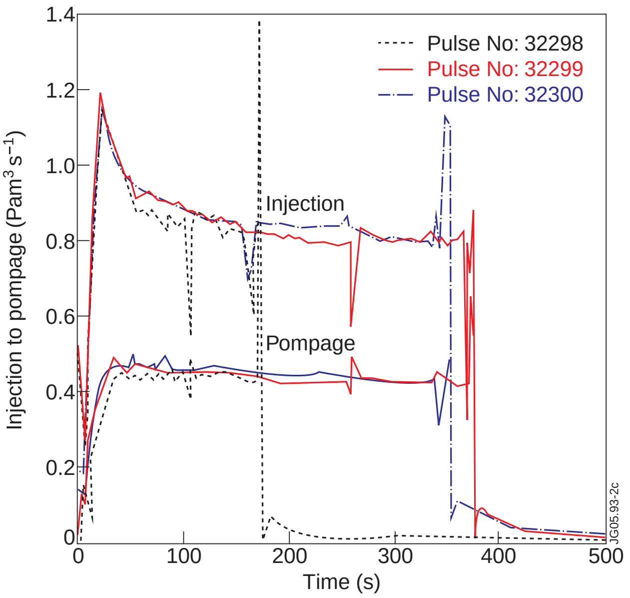

Figure 2: Time evolution of the particle injected and exhausted for a series of long discharges. The retention is the same for all these discharges independently of the previous wall loading.

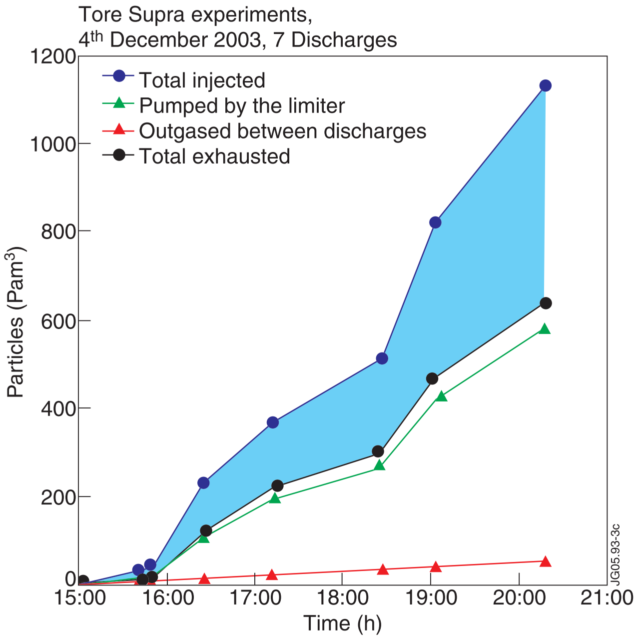

Figure 3: Long term inventory for a series of long discharges in Tore Supra. For long duration, the particle retention is proportional to the plasma duration. The plasma recovery at the end of the discharge is nearly always the same.

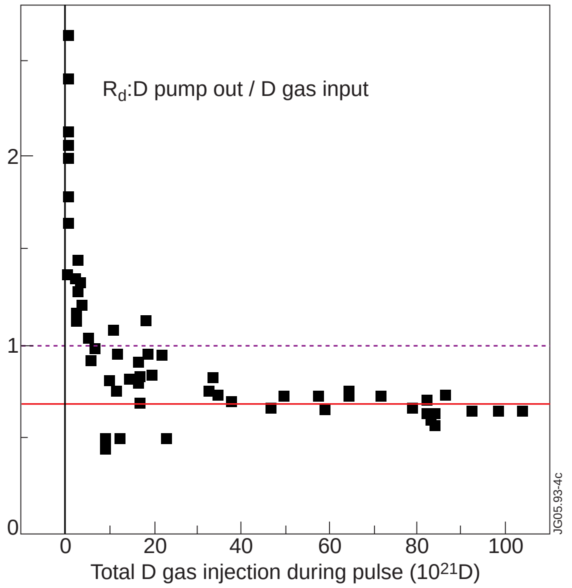

Figure 4: Deuterium gas balance as a function of Injected D gas during plasma phase [6]

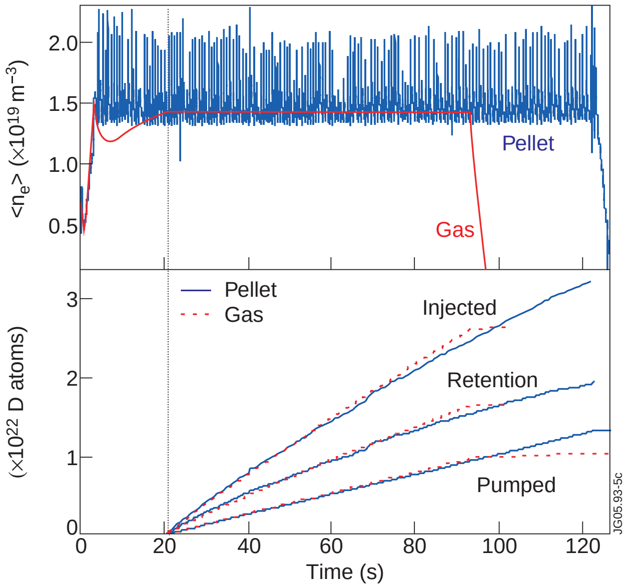

Figure 5: Time evolution of the plasma densities and global particle balances (integrated on the steady state part of the pulses) for gas and pellet fuelling [12].

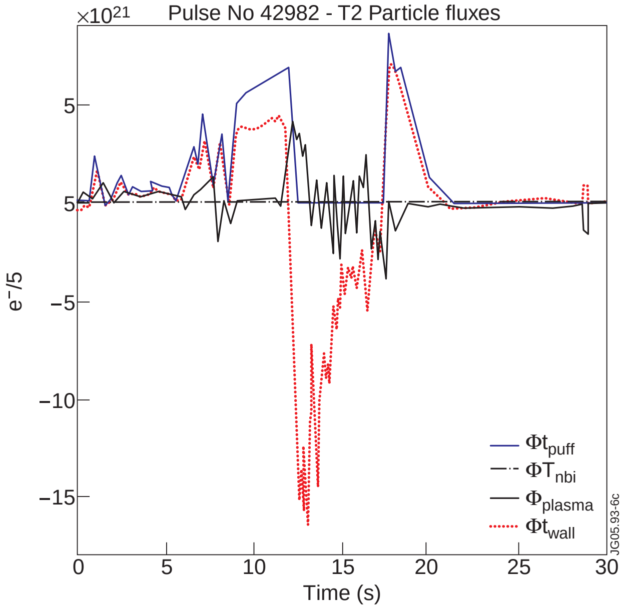

Figure 6: Time evolution of the tritium particle fluxes with gas fueling and NBI fueling during the DTE1 campaign.

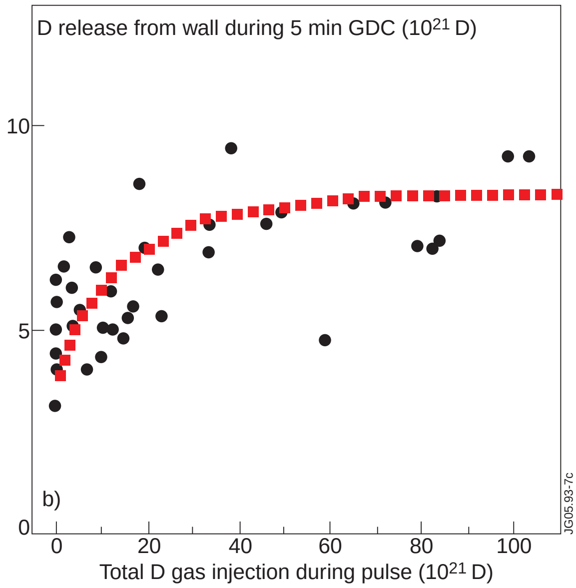

Figure 7: D release from the wall during 5 min of HGD. The particle recovery saturates at ~ 8.10^{21}D independently of the gas injection during the pulses [6].