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Tritium particle balance and retention during DT discharges in JET

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Abstract

The tritium balance based on pressure measurements in the divertor was performed for the DTE1 campaign carried out at JET in 1997. This is a complementary analysis to the integrated tritium inventory already reported for a full day of experiments. The particle balance shows that the T flux retention is about 1.26×10^{21} T s^{-1} during a plasma pulse (~65% of the injected flux). Outgasing between pulses reduces this T inventory to about 30% of the injected fluence. This detailed gas balance also shows that the retention of hydrogen species depends on the plasma isotopic ratio. However, during the D clean-up pulses, the amount of T removed by isotopic exchange is shown to be limited to about 2×10^{23} T. Finally, the total particle balance (D + T) is shown to be independent of the plasma isotopic ratio.

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Keywords: Deuterium inventory; Tritium; Particle balance; Retention; JET

1. Introduction

Particle retention will be a major issue in future fusion devices like ITER in which the amount of in-vessel tritium will be strictly limited for safety considerations [1]. The tritium particle balance will have to be monitored continuously to estimate the real time evolution of the particle retention for the long discharges foreseen in ITER. Since gas balance probably will be the dominant technique used to assess the fuel retention in ITER, it is of high priority to master this technique in today's machines. However, in the present experiments in tokamaks and stellarators with carbon as plasma facing components, the balance between the number of particles injected and exhausted is almost never balanced during the plasma discharge. The DT experiments performed in JET in 1997 are a good opportunity to study simultaneously the tritium retention during the pulses and the implications for the long term retention for the overall campaign. Based on the data from the cryopump regeneration, the tritium inventory has been well documented for full days of operation integrating the three phases: plasma, delay between pulses, and outgasing overnight [2,3]. However, no experimental discrimination between these contributions, particularly during the plasma, have been carried out to analyse the D and T retentions for this campaign.

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In this presentation, T and D particle balances have been performed for all the pulses (~80) of the first phase of the DT experiments in 1997 (5th–11th of June 1997) and extended to the 30 first cleaning pulses (pure D fuelling) after the last 100% T pulse. For all these pulses, the deuterium was fuelled both by gas and one NBI box (octant 4) while the tritium was fuelled only by gas injection from GIM15 (octant 6 mid-plane). Except for the 10 first pulses, the cryopump was activated and single null magnetic configuration was used with the strike points located on the horizontal target plates. From # 41 677 to 41 713 the plasma isotopic ratio T/(T + D) is ~50% (37 pulses – 3 days), 100% (47 pulses – 2 days) from # 41 714 to # 41 760 and finally 100% D (30 pulses analysed – 1 day). The absolute tritium inventory is evaluated from the cryopump regeneration performed at the end of each of the 6 days of experiments [2]. The first section of this contribution details the resulting T and D balance and associated retention over the first phase of the DTE1 campaign while the wall particle reservoir accessible by plasma is discussed in the second section.

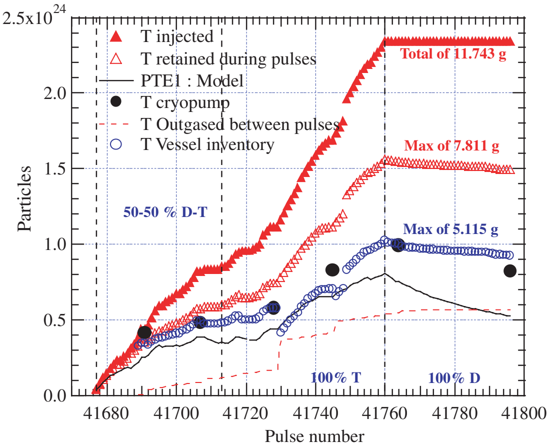

Fig. 1. Cumulative T injected (▲), retained (△) for each discharge and outgasing between discharges (---) as a function of the pulse number. The resulting vessel T inventory is plotted (○) and compared to the T inventory measured by the cryopump regeneration (●) and the PTE based prediction [6] (—).

2. Global particle balance

The particle balance and the associated retention are calculated during the plasma for both D and T using the usual particle balance expression for each species [4]. The D and T fraction in the plasma and in the divertor are evaluated respectively from spectroscopic data and the sub divertor Penning gauge [5], the difference between the two values being generally less than 5%. During the plasma, the particle retention is defined as $(\Gamma_{inj} - \Gamma_{pump})/\Gamma_{inj}$ where Γ_{inj} is the total injection (gas and Neutral beams) and Γ_{pump} is the exhausted flux by both the divertor and the vessel pumps. The cryopump inventory (from cryopump regeneration) and the measured neutral pressure in the divertor, P_{div}, have been taken as references to match the effective pumping speed of the cryopump, allowing to calculate the exhaust by the divertor. The following values result: $S_{Cryo} = 130$ $m^3 s^{-1}$ for X point configuration, $S_{Cryo} = 125$ $m^3 s^{-1}$ in limiter configuration, and finally $S_{vessel} = 49$ $m^3 s^{-1}$ (NBI and Turbo). All these pumping speeds refer to a gas temperature of 320 °C (vessel temperature). The T and D balances have been performed for each pulse. Fig. 1 shows the cumulative particle balance for tritium over the first 80 pulses. Over the six days of operation, the total plasma duration is 1953 s while the divertor operation time is 1237 s.

At the end of the last pulse (# 41 760) with tritium, the total T injected is 2.344×10^{24} T while the total T pumped during the plasma amounts to: 7.85×10^{23} T (34% of the total injected). The total T released between pulses is 5.375×10^{23} T (23% of the total injected), calculated by fitting the resulting neutral pressure in the vessel, P_{vessel}, at the end of the measuring period (~80 s) extrapolating it to the beginning of the next pulse and using P_{vessel} at this time as a minimum value.

The outgasing between pulses plays a significant role in the balance; 23% of the injected T is recovered between the pulses. The average T injection is 1.89×10^{21} T s^{-1} corresponding to an average retention during X point operation of 1.26×10^{21} T s^{-1} (66% of the gas injection). This value is reduced to 7.9×10^{20} T s^{-1} over the full plasma duration (limiter and X point phases) mainly due to the absence of injection during the limiter phase. The outgased flux (measured after the pulse) is 1.03×10^{18} T s^{-1} which is about 3 orders of magnitude lower than the fluxes during plasma operation. However, integrated over 6 days, the total exhausted gas is significant in this overall balance.

The corresponding D balance is plotted on Fig. 2. At the end of the 50/50 DT phase (# 41 713), after 27 pulses without major disruption (only 6 major disruptions occurred during the phase having a negligible effect on the overall particle balance both for the D and T vessel inventories), the total injected D is 4.52×10^{23} with: 4.40×10^{23} D from gas and 1.16×10^{22} D during NBI. The total pumped D during the pulses is 2.18×10^{23} (48% of the total D injected) while the total amount of outgased D is 1.18×10^{23} (26% of the total D injected). The global balance leads to a total retention of 1.16×10^{23} D (26% of the total D injected). During the 100% T phase, only weak D injection is performed for the prefill and for Ti measurements. Consequently the proportion of D in the exhausted mixture is very low and the total D exhausted is negligible in the overall

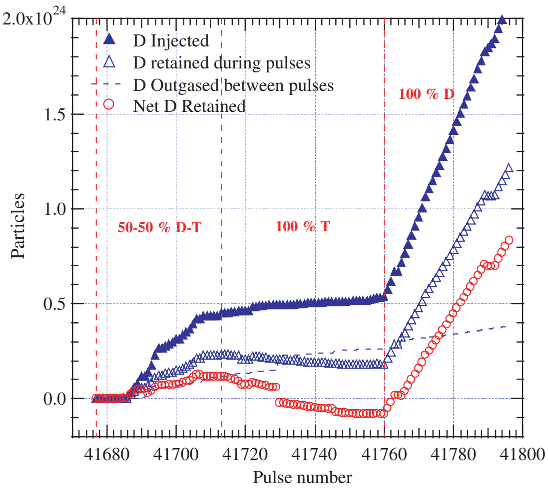

Fig. 2. Cumulative D injected (▲), retained (△) for each discharge, outgasing between discharges (---) and resulting D vessel inventory (○) as a function of the pulse number.

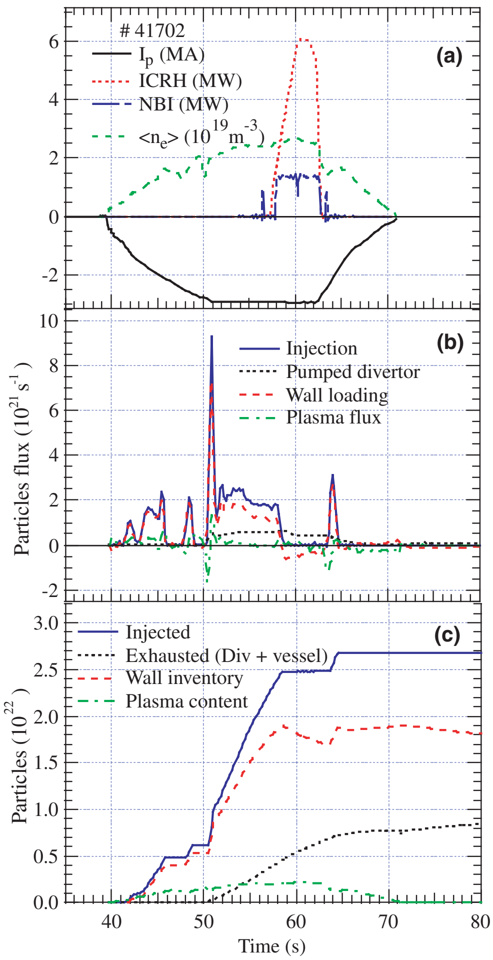

Fig. 3. (a) Typical DT plasma (# 41 702) with an isotopic ratio (T/(T + D)) ~50% an ohmic phase, followed by a simultaneous heating by ICRH and NBI (D+) as a function of time. (b) T Particle fluxes: Injection, exhaust by the divertor, plasma flux and corresponding wall loading. (c) Integrated particle fluxes over the plasma duration.

balance. Indeed, in the 47 pulses of the 100% T phase, with a total D injected of 8.18×10^{22} D, 1.32×10^{23} D are pumped by the divertor and 1.46×10^{23} D are outgased between pulses resulting in a wall depletion of 1.96×10^{23} D. The global D + T balance shows a total increase of 1.85×10^{23} which corresponds to a total retention of 33% of the injected particles. This retention is somewhat higher than the total D + T retention of 15–20% resulting from global balance [3]. Since the T balance (Fig. 1) is in good agreement with the data from the cryopump regeneration, this disagreement could result from the difficulty of estimating the outgased D flux between the experimental sessions. Fig. 3 shows a typical time evolution of a T particle balance. At the beginning of the gas injection a peak in the wall loading is always observed and wall loading always occurs during the gas injection, while it is 'negative' (the wall inventory is depleted) when the gas injection is stopped.

3. Accessible particle reservoir during plasmas

In this global gas balance, no difference was observed between T and D retention except for a few pulses following a change of the isotopic ratio. For example, during the 'pure' D plasmas just after the 100% T phase, a larger D retention is initially observed which then gradually returns to the usual lower value on successive pulses. This is consistent with the fact that the global particle retention (D + T) does not change and that the amount of T removed from pulse to pulse dramatically decreases after ~10 pulses as the isotopic ratio decreases. The corresponding excess of D retention is attributed to isotopic exchange with the tritium that was previously implanted in the wall (the D replaces the T). Fig. 4 shows the tritium exhausted from pulse to pulse during plasma operation (the outgasing is not included in these values) at the beginning of the cleaning phase with ohmic discharges (except for the first pulse which was with 2 MW of ICRH). The peaks on the last pulses originate from application of 6 MW of ICRH. They likely result from both an increase in the recycling flux and therefore an enhanced isotopic exchange simultaneously with a higher surface temperature of the divertor target plates. However, the global trend is recovered very soon (~3 to 4 pulses) showing a wall particle reservoir of $\sim2\times10^{23}$ T that is accessible by plasma operation.

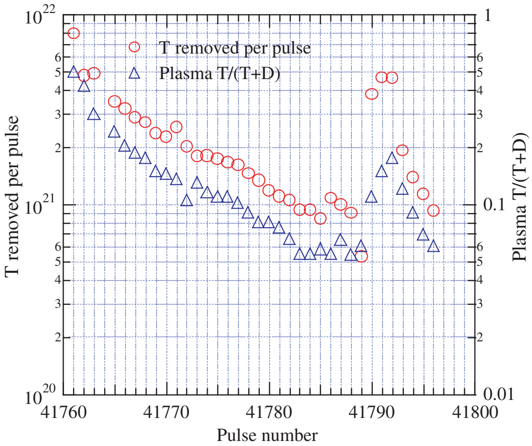

Fig. 4. Tritium atoms removed and plasma isotopic ratio (T/(T + D)) as a function of the pulses performed just after the last 100%T pulse (# 41 760). After 20 pulses, the number of T atoms removed per pulse has dropped by more than 10 in spite of the presence of more than 9.53×10^{23} T particles in the vessel.

The total carbon area in JET is estimated to be $\sim$200 m^2 and this would correspond to a maximum retained fluence of $\sim 10^{21}$ m^{-2} which is consistent for implantation of particles with incident energy of 200 eV before acceleration in the sheath. This reservoir can also be estimated from pulse to pulse by analysing the behaviour of the D retention after the last T pulse. Fig. 5 displays the evolution of the D retention for the first 15 pulses of the cleaning phase. The equilibrium

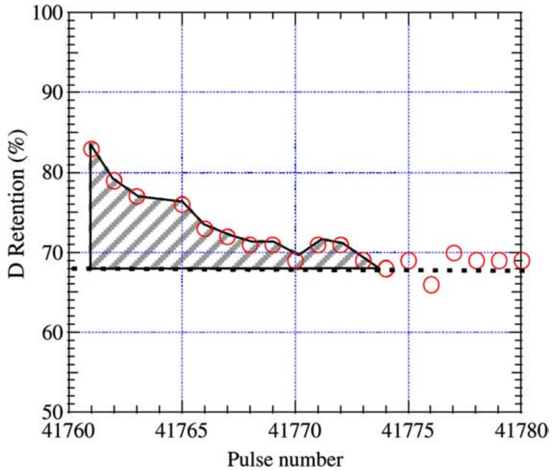

Fig. 5. Evolution the D retention as a function of the pulse performed just after the last 100% T pulse (# 41 760). The decrease of the 'excess' retention is attributed to the isotopic exchange between the D and T implanted in the 200 m^2 of the carbon area.

in the retention process is nearly obtained after $\sim$10 pulses with an X point duration of $\sim$17 s for each pulse. The hashed area corresponds to about 3.0×10^{22} D (compared to the 3.5×10^{22} T removed at the end of the 10th pulse). This retention is not long term since it can be easily recovered or replaced in the wall by isotopic exchange. For the last pulse analysed, the plasma isotopic ratio T/(T + D) is less than 10% while an amount of 9.23×10^{23} T particles (4.624 g of T) is still present in the vessel walls and while the plasma particle content is only in the range of 2–6×10^{21}. Finally, if we assume that the retention results from both isotopic exchange and co-deposition, the total retention by co-deposition at the end of the pulse 41 760 is estimated to be 8.2×10^{23} T. This corresponds to a T retention rate by co-deposition of 4.2×10^{20} s^{-1} if calculated over the total plasma duration or 6.6×10^{20} s^{-1} when taking into account only the X-point duration. For co-deposited layers with a T:C ratio of about 0.5, this corresponds to a carbon flux of $\sim 10^{21}$ s^{-1}.

4. Discussion and conclusions

The wall particle reservoir that is accessible to isotopic exchange is estimated at about 2×10^{23} for hydrogenic species. Equilibrium within the isotopic composition of the wall and the plasma is obtained in about 10 pulses (cumulative plasma duration of 320 s), corresponding to an exchange of $\sim 10^{21}$ D or T s^{-1}. This is a short term retention accessible by plasma operation representing only a modest particle reservoir: 2×10^{23} compared to the 1.02×10^{24} obtained at the end of the pulse 41 760. Co-deposition on the areas of the inner divertor and in particular on the remote areas of the louvers and the tile surfaces adjacent to the pumping gap [3] is the dominant retention mechanism. When the wall is in equilibrium with the plasma in terms of isotopic ratio, the retention is about 66% (1.26×10^{21} T s^{-1}) during plasma operation, while the outgasing between pulses reduces this inventory to about 43% (0.82×10^{21} T s^{-1}) of the total T injected at the end of the last T pulse. The present analysis is based on pressure balance calibrated in situ and thus determined by the accuracy of the gas input measurements and stability of the pressure gauges. Besides the accuracy of the different measuring systems (P_{div}-S_{Cryo} products imply an error of $\sim$10% on the particle balance during the pulse), the importance of the outgasing between pulses particularly over very long durations ($\sim$days) is of the order of 10%. However, for long steady state plasmas, the particle recovery between pulses becomes insignificant since it is not proportional to the plasma duration [7] showing that co-deposition will be very likely the dominant retention process in ITER.

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