

---

EFDA–JET–CP(04)02-12

T Loarer, J Bucalossi, G Matthews, V Philipps  
and JET EFDA Contributors

# Tritium Particle Balance and Retention during DT Discharges in JET



# Tritium Particle Balance and Retention during DT Discharges in JET

T Loarer<sup>1</sup>, J Bucalossi<sup>1</sup>, G Matthews<sup>2</sup>, V Philipps<sup>3</sup> and JET EFDA Contributors\*

<sup>1</sup>Association EURATOM-CEA, DSM-DRFC, CEA Cadarache, 13108 St Paul lez Durance, France.

<sup>2</sup>EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon Oxon OX14 3DB, UK

<sup>3</sup>Association EURATOM / FZJ, Forschungszentrum Jülich Institut für Plasmaphysik 52425 Jülich, Germany

\* See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",  
Fusion Energy 2002 (Proc. 19<sup>th</sup> IAEA Fusion Energy Conference, Lyon (2002)).

Preprint of Paper to be submitted for publication in Proceedings of the  
16th PSI Conference,  
(Portland Maine, USA 24-28 May 2004)

“This document is intended for publication in the open literature. It is made available on the understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original when applicable, or without the consent of the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.”

“Enquiries about Copyright and reproduction should be addressed to the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.”

## ABSTRACT

The tritium balance based on pressure measurements has been performed on a shot by shot analysis during the plasma operations of the DTE1 campaign carried out at JET in 1997. This gives 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 was of the order of about  $1.26 \cdot 10^{21} \text{ T s}^{-1}$  during the plasma operations (~65% of the injected flux). The outgassing between pulses reduces this T inventory to about 30% of the injection. This detailed gas balance shows also 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  $2 \cdot 10^{23}$  particles. Finally, the total particle balance (D+T) is shown to be independent the plasma isotopic ratio.

## 1. INTRODUCTION

Particle retention is a major constraint for future fusion devices like ITER in which the amount of tritium will be strictly limited for safety considerations [1]. A tritium particle balance will have to be carried out permanently to estimate the particle retention in real time for the long discharges foreseen in ITER. The evaluation of gas balance data in present tokamaks is of high priority to establish the technique and data base for ITER, for which gas balances will be probably the dominant technique to assess the fuel retention. However, in the present experiments in tokamaks and stellarators with carbon as plasma facing components, the balance between the particles injected and the particles exhausted is nearly never equilibrated during the discharge. The DT experiments performed in JET in 1997 are a good opportunity to study simultaneously the tritium retention during the discharges 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 the entire days of operation integrating the three phases: plasma, delay between pulses and overnight of outgassing [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.

In this presentation, T and D particle balances have been performed for all the discharges (~80) of the first phase of the DT experiments in 1997 (5th to 11th of June 1997) and extended to the 30 first cleaning pulses (pure D<sub>2</sub> fuelling) after the last 100% T pulse. For all these discharges, 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 Pulse No:41677 to 41713 the plasma isotopic ratio T/(T+D) is 50% (37 pulses – 3 days), 100% (47 pulses – 2 days) from Pulse No:41714 to Pulse No:41760 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 for the first DT

phase [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 second section details the wall particle reservoir by plasma operations.

## 2. GLOBAL PARTICLE BALANCE

The particle balance and the associated retention are calculated during the plasma for both D and T using the classical 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 two values being generally very close. During the plasma, the particle retention is defined as  $(\Gamma_{inj} - \Gamma_{pump})/\Gamma_{inj}$  where  $\Gamma_{inj}$  is the total injection (gas and Neutral beams) and  $\Gamma_{pump}$  is the exhausted flux by both the divertor and the vessel. The cryopump inventory (cryopump regeneration) and the measured neutral pressure have been taken as reference to match the effective pumping speed of the cryopump, allowing to calculate the exhaust. The following values result  $S_{Cryo} = 130 \text{ m}^3\text{s}^{-1}$  for X point configuration,  $S_{Cryo} = 125 \text{ m}^3\text{s}^{-1}$  in limiter configuration and finally  $S_{vessel} = 49 \text{ m}^3\text{s}^{-1}$  (NBI and Turbo). All these pumping speed refer to a gas temperature of  $320^\circ\text{C}$ . The T and D balances have been performed for each pulse. Figure 1 shows the cumulated particle balances for the tritium over the first 80 pulses. Over the six days of operations, the total plasma duration is 1953.4 seconds while the divertor operation time is 1237.3 seconds.

At the end of the last T pulse (Pulse No: 41760), the total T injected is  $2.344 \cdot 10^{24}\text{T}$  while the total T pumped during the plasma amounts to:  $7.85 \cdot 10^{23} \text{ T}$  (34%). The total T released between pulses is  $5.375 \cdot 10^{23} \text{ T}$  (23%), calculated by fitting the resulting neutral pressure in the vessel,  $P_{vessel}$ , at the end of the measuring time ( $\sim 80 \text{ s}$ ) and 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 T injected is recovered in between the pulses. The averaged T injection is  $1.89 \cdot 10^{21} \text{ T s}^{-1}$  corresponding to an averaged retention during X point operation of  $1.26 \cdot 10^{21} \text{ T s}^{-1}$  (66% of the injection). This value is reduced to  $7.9 \cdot 10^{20} \text{ T s}^{-1}$  over the full plasma duration. The outgased flux (after the pulse) is  $1.03 \cdot 10^{18} \text{ T s}^{-1}$  which is about 3 orders of magnitude lower than the fluxes during the plasma. However, integrated over 6 days, the total exhausted gas becomes significant in this overall balance.

The corresponding D balance is plotted on figure 2. At the end of the 50/50 DT phase discharges (Pulse No: 41713), after 27 “good” pulses, the total injected D is  $4.52 \cdot 10^{23}$  with:  $4.40 \cdot 10^{23}\text{D}$  from gas and  $1.16 \cdot 10^{22}\text{D}$  during NBI. The total pumped D during the pulses is  $2.18 \cdot 10^{23}$  (48%) while the total amount of outgased D is  $1.18 \cdot 10^{23}$  (26%). The global balance leads to a total retention of  $1.16 \cdot 10^{23}\text{D}$  (26%). During the 100% T phase, only weak D injection are performed for the prefill and for Ti measurements, but the proportion of D in the exhausted mixture is very poor and the total D exhausted is low. Indeed, in the 47 pulses with a total D injected of  $5.33 \cdot 10^{23} \text{ D}$ ,  $3.5 \cdot 10^{23} \text{ D}$  are pumped by the divertor and  $2.64 \cdot 10^{23} \text{ D}$  are outgased between pulses resulting in a wall depletion of  $8.1 \cdot 10^{22} \text{ D}$ . The global D+T balance shows a total increase of  $1.85 \cdot 10^{23}$  which corresponds to a

total retention of 33% of the total particle injected. This retention is somewhat higher than the total retention of 15-20% resulting from global balance [3]. Since the T balance is in good agreement with the data, this underestimation could result from the outgased flux between the days of experiments. On figure 3 a typical time evolution of a T particle balance is plotted. 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 has been observed between T and D retention except when the isotopic ratio is changed. Indeed, during the “pure” D plasmas operated just after the 100% T phase, a larger D retention results and recover from pulse to pulse to the usual value. 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 the isotopic exchange with the wall, the T is replaced by D. Figure 4 shows the tritium exhausted from pulse to pulse during the 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 (2MW of ICRH). The peaks for the last pulses originate from application of 6MW of ICRH. It results likely 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 showing a wall particle reservoir of  $\sim 2 \cdot 10^{23}$  T that is accessible by plasma operation. The total carbon area in JET is estimated to be  $\sim 200\text{m}^2$  and this would corresponds to a maximum retained fluence of  $\sim 10^{21}\text{m}^{-2}$  which is consistent for implantation of particles with incident energy of 200eV before acceleration in the sheath. This reservoir can also be estimated from pulse to pulse by analysing the the behaviour of the D retention after the last T pulse. Figure 5 displays the evolution of the D retention for the 15 first pulses of the cleaning phase. The equilibrium is nearly obtained after ~10 pulses with an X point duration of ~ 17sec for each pulse. The hachured area corresponds to about  $3.0 \cdot 10^{22}\text{D}$  (compared to the  $3.5 \cdot 10^{22}\text{T}$  removed at the end of the 10<sup>th</sup> 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  $9.23 \cdot 10^{23}$  T particles (4.624 g of T) is still present in the vessel walls, while the plasma content is only in the range of  $2\text{-}6 \cdot 10^{21}$ . Finally, if we assume that the retention is resulting from both isotopic exchange and co deposition, the total retention by co-deposition at the end of the pulse 41760 is estimated to be  $8.2 \cdot 10^{23}$  T. This corresponds to a T retention rate by co deposition of  $4.2 \cdot 10^{20}\text{s}^{-1}$  if calculated over the total plasma duration or  $6.6 \cdot 10^{20}\text{s}^{-1}$  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  $\sim 10^{21}\text{s}^{-1}$ .

## DISCUSSION AND CONCLUSIONS

The wall particle reservoir that is accessible to isotopic exchange is estimated to about  $2 \cdot 10^{23}$  for hydrogenic species. The equilibrium within the isotopic plasma composition is obtained in about 10 pulses (cumulative plasma duration of 320s), corresponding to an exchange of  $\sim 10^{21}$  D or T  $s^{-1}$ . This is a short term retention accessible by plasma operations representing only a very low particle reservoir:  $2 \cdot 10^{23}$  compared to the  $1.02 \cdot 10^{24}$  obtained at the end of the Pulse No:41760. The codeposition at 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% ( $1.26 \cdot 10^{21}$  Ts<sup>-1</sup>) during the plasma operations, while the outgasing between pulses reduces this inventory to only 43% ( $0.82 \cdot 10^{21}$  Ts<sup>-1</sup>) of the total T injected at the end of the last T pulse. However, for long plasma duration, the recovery between discharges becomes less important since it is not proportional to the plasma duration [6] showing that co deposition will be very likely the dominant retention process in ITER.

## REFERENCES

- [1]. G. Federici, C. Skinner, J.N. Brooks et al., Nuclear Fusion, Vol.41, Vol.12R (2001).
- [2]. Ph Andrew et al. Fusion Engineering and Design **47** (1999) 233-245.
- [3]. P Coad, Ph Andrew and A Peacock, Physica Scripta. Vol. T81, 7-12, 1999.
- [4]. J Bucalossi, T Loarer et al., 28<sup>th</sup> EPS Conf., Funchal, ECA, Vol.25A (2001) 1629-1632.
- [5]. D Hillis et al., Fus. Eng. Design, 34/35, (1997) **347**.
- [6]. D Van Houtte, G. Martin, A. Bécoulet et al., Nucl. Fusion **44** (May 2004) L11-L15



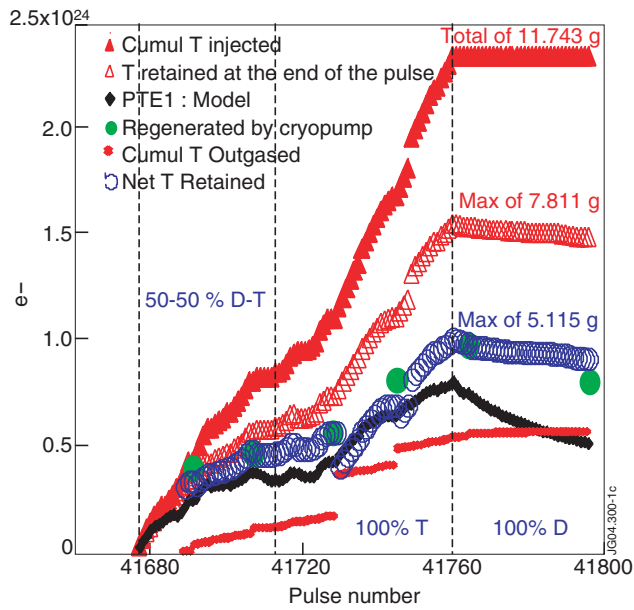


Figure 1: Cumulative  $T$  injected ( $\square$ ), retained ( $\Delta$ ) for each discharge and outgasing between discharges ( $\times$ ) as a function of the pulse number. The resulting vessel  $T$  inventory is plotted ( $\square$ ) and can be compared to both the  $T$  inventory measured by the cryopump regeneration ( $\circ$ ) and the PTE model ( $\diamond$ ).

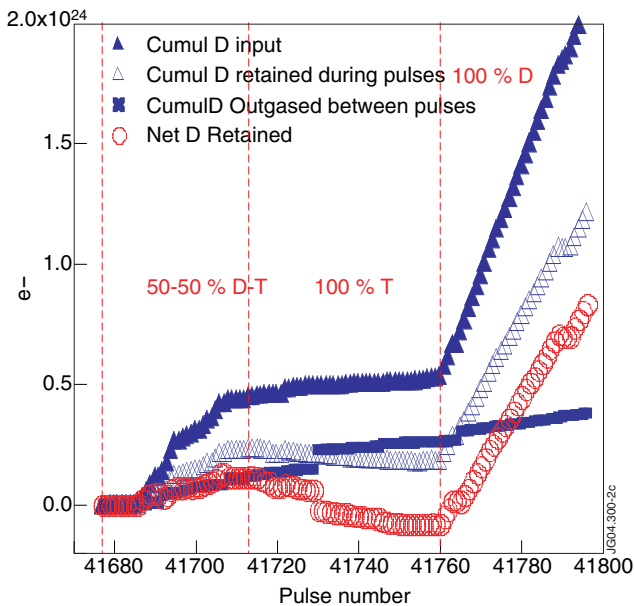


Figure 2: Cumulative  $D$  injected ( $\square$ ), retained ( $\Delta$ ) for each discharge, outgasing between discharges ( $\times$ ) and resulting  $D$  vessel inventory ( $\square$ ) as a function of the pulse number.

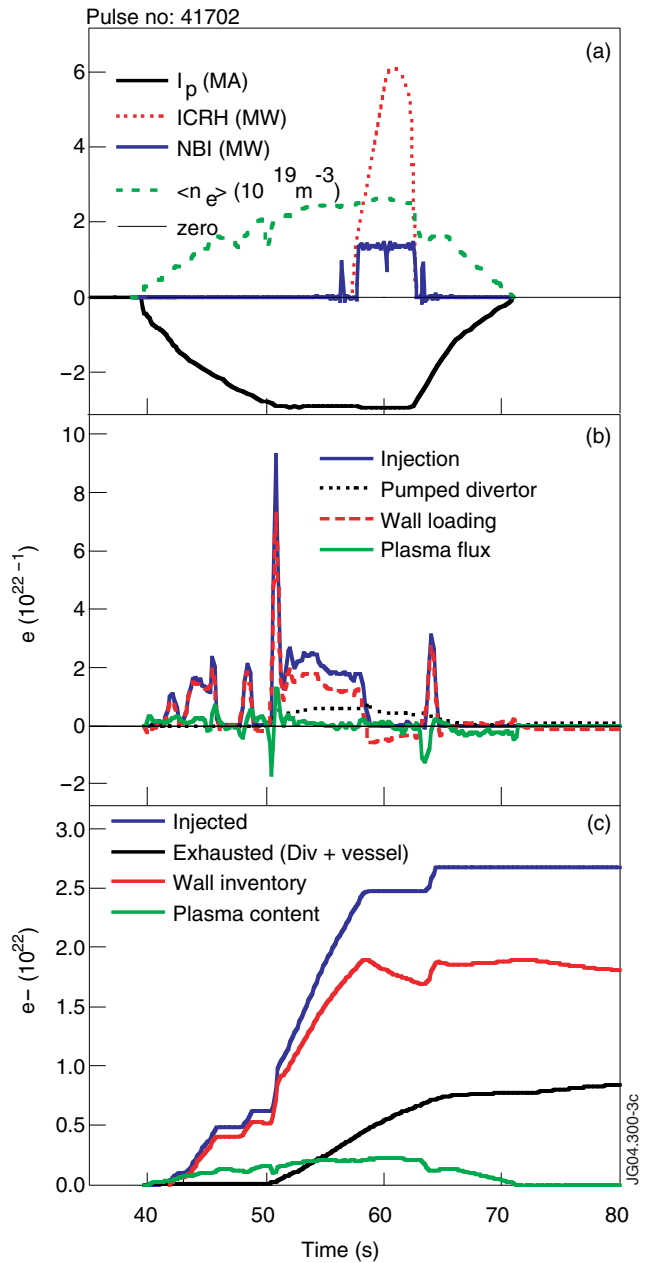
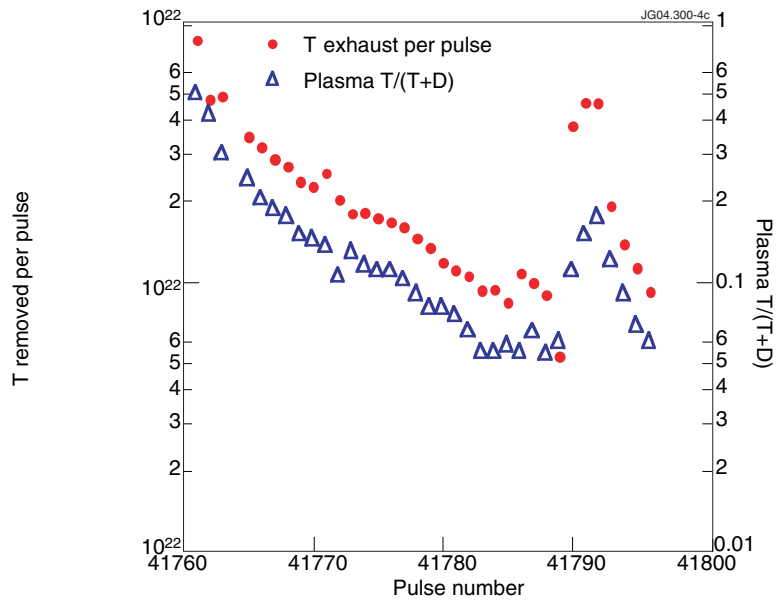
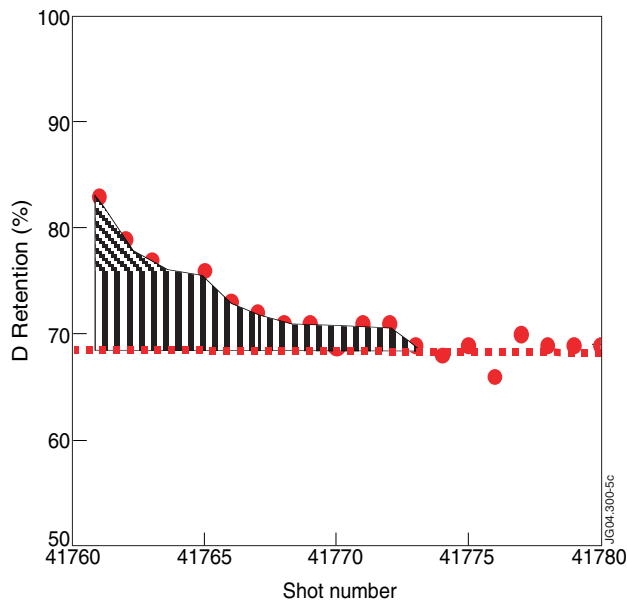


Figure 3: a) Typical DT plasma (Pulse No: 41702) with an isotopic ratio ( $T/(T+D)$ )~50% an ohmic phase, flowed by a simultaneous heating by ICRH and NBI ( $D^+$ ) as a function of time. b)  $T$  Particle fluxes: Injection, exhaust, density variation and corresponding wall loading. c) Integrated particle fluxes over the plasma duration.



**Figure 4:** Tritium removed and plasma isotopic ratio ( $T/(T+D)$ ) as a function of the discharges performed just after the last 100%T pulse (Pulse No: 41760). After 20 pulses, the T removed per discharge has dropped by more than 10 in spite of the presence of more than  $9.53 \cdot 10^{23}$  T particles in the vessel.



**Figure 5:** Evolution the D retention as a function of the discharge performed just after the last 100%T pulse (Pulse No: 41760). The decrease of the “excess” retention is attributed to the isotopic exchange between the D and T implanted in the  $200\text{m}^2$  of the carbon area.