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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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## 1. INTRODUCTION

In ITER, a retention of 10% of the tritium injected (T injection rate ~$5\times10^{22}$T $s^{-1}$) during the 400sec of burning phase would lead to the limit of 350g (nuclear licensing) in only 35 discharges. Thus the evaluation of fuel retention in present tokamaks is of high priority to establish a database for ITER, for which gas balance will be the dominant technique used to assess the fuel retention. In order to achieve high accuracy and to minimise the contribution from previous experiments (history), the overall particle balance has been studied in JET in a series of repetitive and identical discharges. The particle retention behaviour has been analysed for L and H-modes (type III and I ELMs). The resulting fuel retentions for these different plasma scenarios are reported in this paper and will be used as a reference for the comparison with the long term retention resulting from the use of different materials for plasma facing components for the future ITER-like Wall project of JET [1].

## 2. EXPERIMENTS

The two basic mechanisms for long term fuel retention are the deep implantation (diffusion/migration in the bulk material) and the codeposition of D with carbon and/or Berylium. In JET (and also in other carbon devices) codeposition is suspected to dominate the long term retention as it is also expected for the Be/W wall in JET and in ITER.

A series of consecutive and repetitive discharges has been performed in L mode, Type III and Type I ELMing H modes with the following main parameters: $I_p$ = 2MA, $B_T$ = 2.4T, $\langle n_e \rangle = 4.5\times10^{19}m^{-3}$, gas rate~0.6-$1.8\times10^{22}$ $Ds^{-1}$ with 10+3MW of NBI and ICRH respectively for the type I ELMy H mode (5 pulses), 6MW of ICRH only for the type III ELM experiments (13 pulses) and 1.5MW of ICRH only for the L-mode experiments (6 pulses). For all the experiments, active pumping was ensured by the divertor cryopump only (all main chamber pumps closed) and its regeneration (to liquid nitrogen temperature) before and after the series (~at least 1/2 hour after the last pulse) thus allows a direct measure of the long term retention. The accuracy of the calibrated gas injection and regeneration in the active gas handling system at JET from the cryopumps has been measured in dry runs to be better than 1.2%. In all of the series, repetitive and reproducible plasma conditions were obtained for all shots. There was no particular wall conditioning before the experiments (neither He glow discharge cleaning, nor Beryllium evaporation) and disruption were also avoided for all the series, except for one shot of the series of type I ELMy H-modes, which however did not led to a higher outgassing and did not affect the conclusions. The overall results for these three different scenarios are reported in table I. When averaged over the heating phase, the long term retention is ~$1.74\times10^{21}Ds^{-1}$ for the L-mode, 1.3~$\times10^{21}Ds^{-1}$ for the Type III ELMing H-mode and $2.83\times10^{21}Ds^{-1}$ for the Type I ELMs. This corresponds to long term retention fractions of ~11%, 18% and 13% respectively of the injected flux.

## 3. PARTICLE FLUX

In this analysis, the short term retention (dynamic retention) is supposed to be fully recovered from the outgassing flux occurring between pulses [2]. The particle injection (gas and NBI) is calibrated whilst the sum of the "Pumped flux" during the pulse and of the "Short term retention" (outgassed flux between pulses) corresponds to the amount of particles recovered from the cryopump regeneration. It is therefore possible to separate the contributions of the long term and short term retention in the equation of the particle fluxes

**Injection = Long Term Retention + Short Term Retention + Pumped flux (1)**

Figure 1 shows the particle fluxes for a typical pulse of the L mode series. At 15 sec, the overall retention is $6.5\times10^{21}Ds^{-1}$ and results from the sum of the long term retention $1.74\times10^{21}Ds^{-1}$ (see table I) and of the dynamic retention ~ $4.76\times10^{21}Ds^{-1}$. Ten second later, at 25 sec, the total retention has decreased to $4.65\times10^{21}Ds^{-1}$ due to the drop of the dynamic retention to ~$2.91\times10^{21}Ds^{-1}$.

In these series of pulse the dynamic retention drops as a function of time (by ~50% in 10sec) for all the discharges. The same behaviour is observed for the type III ELMy H-mode, where the long term retention rate is $1.31\times10^{21}Ds^{-1}$. Compared to L mode, this long term retention is lower by ~25% but the gas injection is also lower by a factor of 3. This suggests that the retention depends both on the gas injection rate and on the plasma scenario (ELMs). This is supported by the results of the Type I ELMy H-mode as shown in figure 2, displaying the typical particle fluxes for these discharges. At 16sec, 2sec after the beginning of the heating (13MW of total input power and ELM energy ~150kJ), the short and long term retention are close, respectively ~ 45 and 55%. However, the drop of the dynamic retention occurs very quickly compared to L-mode (and type III), and after 6sec the retention is totally dominated by the long term retention. The D$\alpha$ signals show that the recycling flux in the inner leg and horizontal region are higher by 6 and 2 respectively when moving from L-mode to Type I ELMy H-mode. This strong increase of the recycling flux can explain the faster saturation of the dynamic retention for the Type I ELMs. For the Type III ELMy H-mode, the D$\alpha$ signals are of the same order as for the L-mode. From these three scenarios, the long term retention exhibits a strong increase with the gas injection, the recycling flux and the ELM energy. This increase of the long term retention is consistent with the enhanced carbon transport within the SOL resulting from the higher erosion of the carbon of the plasma facing components with the recycling flux and the ELM energy. This is supported by the exponential increase of the carbon deposition observed in the inner divertor region with increasing ELM energy from thermal decomposition of co-deposited layers [3].

Finally, this series of experiments also confirms [2] that within a factor of two to three, the number of particles is always in the range ~$1\text{-}3\times10^{22}D$. This fraction of particles recovered after the pulse is always larger than the plasma content (typical JET plasmas ~ $0.5\times10^{22}D$), but it appears to be nearly independent of the type of discharge (L or H modes), the energy of the ELMs, the quantity of particles injected and the history of the retention.

## SUMMARY

The fuel retention has been studied out in JET in L mode, Type III and Type I ELMy H-modes using gas balance in series of repetitive pulses with an overall accuracy of about 1.2%. The short term (dynamic) retention is important for both L mode and Type III ELMy H-mode over the heating phases (respectively 13 and 17sec) but decreases already significantly during the shot. It becomes small already after 6sec for the Type I ELMy H-mode conditions. In all the cases, the recovery after the pulse contributes for a weak part in the gas balance and in the overall fuel retention. The absolute long term fuel retention (on the time basis of typically 5 hours) for the different plasma conditions is between 1.3 and $2.8\times10^{21}Ds^{-1}$ (averaged over the plasma heating time) and in reasonable agreement with the value deduced from post mortem tile analysis of about $5\times10^{20}Ds^{-1}$considering the additional long term outgassing, conditioning and disruptions included in the post mortem analysis. The increase of the long term retention observed from L mode to Type I ELMy H-mode is associated to the increase of the recycling flux and the ELM energy. This larger long term retention is attributed to an enhanced carbon erosion and transport in the SOL leading to stronger carbon deposition and fuel codeposition. The results confirm the strong concerns about fuel retention in a carbon clad tokamak and a possible full carbon wall ITER which could reach the T-inventory limit in only a small number of high performance shots. A reasonable ITER operation time depends thus on a significant reduced T codeposition under the different ITER material conditions (which has to be confirmed in a relevant tokamak experiment such as the JET ILW project) and an effective routine T removal technique.

## REFERENCES

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[3]. A. Kreter, G Esser, private communication.

| | **Total Injected** | **Total recovered (cryopump regeneration)** | **Long term Retention (heating phase)** |
|---|---|---|---|
| **L Mode** | $1.35\ 10^{24}$ D (4.51g) | $1.208\ 10^{24}$ D (3.95 g) | $1.74\times10^{21}$Ds-1 (81s) |
| **H-mode Type III** | $1.48\ 10^{24}$ D (4.95g) | $2.611\ 10^{24}$ D (4.08 g) | $1.31\times10^{21}$Ds-1 (221s) |
| **H-mode Type I** | $7.17\ 10^{23}$ D (2.4g) | $6.266 10^{23}$ D (2.09 g) | $2.83\times10^{21}$Ds-1 (32s) |

*Table I: Total number of particles injected, recovered from cryopump regeneration and long term retention, averaged over the heating phase, for the three series of experiments in L mode, Type III and Type I ELMy H-mode.*

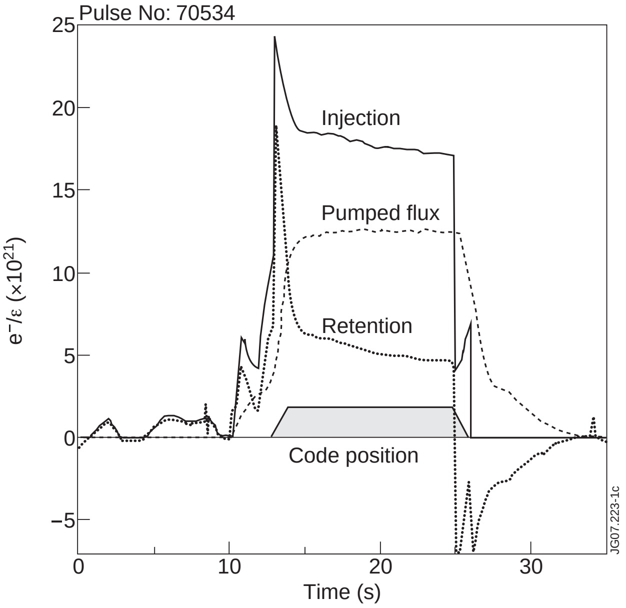


*Figure 1: Particle fluxes for a typical pulse of the L mode series. The grey area represents the long term retention averaged over the heating phase. The difference between the red plot and the top of the grey area represents the dynamic retention.*

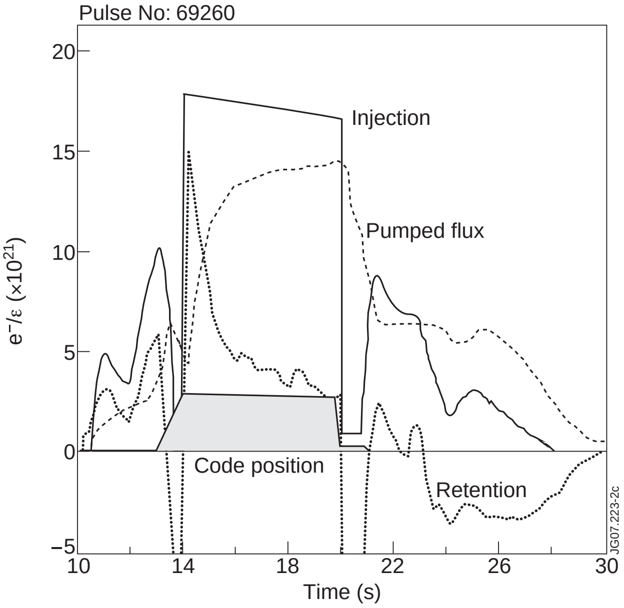


*Figure 2: Particle fluxes for a typical pulse of the Type I ELMy H-mode series. The long term retention dominates the retention after 6 sec.*