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ABSTRACT

Long term fuel retention experiments have been performed in JET with the ITER- Like Wall (JET-ILW) and compared with references in carbon in ohmic, L and H-mode conditions. The long term retention is evaluated through global gas balance for series of repetitive pulses (10 to 25) carried out over a full day of experiments. For ohmic plasma, a retention rate of $3\text{-}5\times10^{19}Ds^{-1}$ is obtained which has to be compared to $1\text{-}2\times10^{20}Ds^{-1}$ in carbon. For L mode, the retention exhibits also a drop from $1\times10^{21}Ds^{-1}$ to $4\text{-}8\times10^{19}Ds^{-1}$. Finally for Type III and type I ELMy H-mode, the retention decreases from $1.4\times10^{21}Ds^{-1}$ to $7.7\times10^{19}Ds^{-1}$ and from $1.7\times10^{21}Ds^{-1}$ to $2.7\times10^{20}Ds^{-1}$ respectively. Retention rates with the JET-ILW exhibits a decrease by a factor 10 compared to carbon attributed to a reduction of carbon impurities and less fuel content in Be codeposition. Compared to carbon, extrapolation to ITER exhibits an increase of a factor of 10 of the predicted number of full performance 400s discharge before reaching the safety limit of 700g of T retention.

1. INTRODUCTION

Long term retention in the Plasma-Facing Components (PFCs) is a critical issue since it must be kept below a safety limit of 700g of mobilise T in a fusion device like ITER. Therefore, particle control is essential for the next step fusion machines: particle injection and extraction systems must regulate the D-T fuel densities, exhaust helium ash, and particularly minimize the tritium vessel inventory. In JET, when moving from full carbon PFCs to the metallic ITER-Like Wall (JET-ILW) [**1**] (First wall in Beryllium and divertor in Tungsten) one of the main objective was to evaluate the reduction of the fuel retention dominantly associated to carbon through co-deposition in remote areas. Prior to the change of the materials, series of experiments on fuel retention were carried out in carbon to be used as references for comparison with the JET-ILW. The main objectives of these series of experiments were to quantify the long term fuel retention, build a reference in carbon and quantify the benefit of the metallic PFCs compared to C. In this study the retention rates obtained for different plasma scenarios carried out with the JET-ILW are compared with the reference experiments performed with the JET-C configuration [**2**]. Under carbon wall conditions, post mortem analysis and gas balance reference experiments showed that co-deposition in remote areas such as the divertor pumping throats was the main and dominant retention mechanism [**3**]. It is worth noting that codeposition is also expected with beryllium, since the first wall in Be will also experience erosion, transport through the SOL and finally codeposition identified as a safety issue since this retention process is proportional to the discharge duration [**4**]. In the case of the JET-ILW, a reduction of the C content by at least one order of magnitude has been measured [**5**] and thus co-deposited with C will no longer dominate the long term fuel retention. Therefore the remaining long term retention by codeposition by Be is expected to be much lower than in JET-CFC since less D is trapped in the Be deposits with also a strong decrease with temperature. Indeed, in the range 100-200°C, the ratio D/Be is about 10 times lower than for the carbon [**6**] whilst it is more than 100 times lower for W. Also, from previous experiments in JET, thick carbon layers have been found in the shadowed subdivertor region but with no, or a small amount, of Be although many Be evaporation were performed and significant C deposit were found in this region with very high D/C ratio up to 1. Due to this reduced long range transport which was caused in case of C by chemical sputtering to shadowed areas [**7**] the resulting retention with Be should significantly drop.

For tungsten, according to ASDEX-Upgrade (AUG) experiments, the codeposition by W is very low and the long term retention is dominated by implantation [**8**] down to a level lower than 1%. In JET the possible retention in the mixed materials (W-Be alloys) and/or Beryllium oxides are not yet assessed and will be clarified with complementary results through post mortem analysis. The samples will be removed after the campaign and analysis will be performed for the determination of the location of the D retained and for consolidation of the global retention with the JET-ILW. The short term retention dynamic retention) is also assessed complementary. The dynamic retention is a transient behaviour characterising the ability of the material to store additional amount of hydrogen, even if the material is saturated, under large particle impact. This additional amount is thermally released after the shot and appears as neutral outgassing after the discharge. The comparison of long term outgassing, dynamic retention and release of carbon and Be/W PFCs are reported in details in [**9**].

In the first section, the integral gas balance used for the evaluation of the retention is described whilst the main results for comparison of the fuel retention in C and Be/W are discussed in section three. The section four focuses on the retention occurring during the divertor and heating phase, whilst a preliminary extrapolation is proposed for ITER.

2. GAS BALANCE

On JET, the divertor is equipped with a cryopump (PD) which can be regenerated after each session (~10 hours). For the fuel retention experiments, sets of identical discharges (typically series of 15-20 repetitive discharges), without intershot conditioning, are performed to avoid history effects. The regeneration of the cryopump before and at the end of the session allows the total gas pumped by the PD (only active pumping system used for most of the reported experiments) during session to be known. This amount corresponds to the particles exhausted during the plasma operation and also released by outgassing in between discharges (recovery of the dynamic retention). Based on this procedure, the long term retention can be evaluated from the difference of the total injection minus the amount obtained through the PD regeneration; the dynamic part cancels for the JET-ILW completely out [**9**]. Also, using the neutral pressure measurements in the vacuum chamber, it is possible to determine the amount of particles pumped by the PD in between the pulses. Therefore, from the total amount regenerated from the PD, it is possible to deduce the amount pumped during the discharge and to correlate the retention to the plasma scenario. Indeed, it is possible to reconstruct the particle fluxes pumped during plasma using the neutral pressure measurement provided by the gauge located in the sub-divertor region close to the cryopump. It is worth noting that in JET (Carbon and ILW) the plasma duration in divertor and heating phase are not long enough for reaching steady state configurations in terms of particle fluxes. In these conditions, the transient phases (beginning and end of the divertor and heating phases) have a non-negligible effect on the resulting particles fluxes and overestimate the retention flux since it includes both the dynamic and long term retention. One of the main issues for the gas balance analysis integrated over a full day of experiments is the error generated through this method. Indeed, the long term retention results from the difference of large numbers. As an example, for a session on Type III ELMy H-mode: 21 pulses were performed, cumulating total plasma duration of about 10 min over a session of 10 hours. The total amount of particles injected was 1.217×10^{24}D and the total recovered $1.186\text{x}10^{24}$D, leading to a difference of only 3.1×10^{22}D. Particular efforts have been dedicated for improving the accuracy of the gas balance with regular calibrated gas injection (GIM) and recovery using the Active Gas Handling System (AGHS) of JET. Based on cross calibrations of the amount injected and recovered (w/o plasma), neutral pressure measurements in main chamber (Penning gauges), in the subdivertor (Baratron gauges type) and cross correlation of these pressure gauges have been performed. Finally, a careful analysis of the volumes involved and the temperature for the GIMs and the AGHS have been taken into account. Indeed, a temperature difference of "only" 7K (293 to 300K) corresponds to a difference of 2.5% in terms of number of particles. Based on these series of calibrations, the global accuracy of the injection and the recovery of the gas balance over a session is in the range of 1%. Finally, it is worth noting that for all the series of experiments and for both JET-C and JET-ILW configurations (except ohmic discharges for JET-ILW) since no overnight outgassing can be taken into account, the long term retention determined through the gas balance procedure represents an upper value. Indeed, for the reported experiments with the JET-ILW, the total amount of particles retained in the vessel at the end of the experimental session varies in between 3 and 9×10^{22}D (depending on the number of discharges performed during the session and also if the PD is warm or cold) whilst the additional recovery over a full night (12 hours) can be estimated in the range of 10^{22}D, compared to the 1.5-3×10^{22}D recovered in between discharges (~20 to 30 min). For carbon, although the amount released over a full night was in the same range, the overnight recovery was not so significant in the overall balance since the retention with JET-C ranged from 1 to 3×10^{23}D.

3. MAIN RESULTS

The main results of long term fuel retention deduced from gas balance studies for JET-ILW are compared with JET-C in **figure 1.** The retention rate is normalized to the time spent in the divertor configuration which is representative of the plasma wall interaction duration. For all the plasma scenarios the retention rate exhibits a significant drop by about a factor of 10. As shown on this plot, some experiments have also been carried without active pumping (PD warm) and similar retention rates are obtained compared to experiments performed with active pumping. It is worth noting that without PD, during the steady state phase obtained for the plasma density, the retention rate is equal to the gas flow required for maintaining the plasma density constant. In addition, in the absence of active pumping, a lower gas throughput is required (~ 5 times less) allowing for a better statistic for plasma scenario. During these experiments, only the turbo pumps of the vessel were activated allowing for the outgassed particles to be recovered at the end and in between the discharges. For these experiments, the pumped gas through the turbo pumps was continuously collected in the AGHS all along the session. From ohmic to L-mode and ELMy H-mode, an increase of the retention rate is observed, but the maximum obtained is in the range of $2.7\times10^{20}Ds^{-1}$ for the type I ELMy H-mode with 11MW of NBI of input power. The results presented for the series of ohmic experiments correspond to five consecutive days, including three days of plasma operation with 43 successful ohmic discharges cumulating more than 16 min of plasma in X-point and two days of outgassing. Therefore, since the plasma scenario in ohmic is very close to the L-mode (only 0.5MW of ICRH heating), the lower retention is significant compared to L-mode and can be attributed to the two days of recovery.

As for carbon, the plasma scenario does not seem to strongly impact the retention rate and from ohmic to type I ELMy H-mode the increase in the retention rate is of a factor of 2. In **table I**, the retention rated obtained with JET-C and JET-ILW are compared. It is worth noting that for the type I ELMy H-mode, although the input power/energy was modest (11MW during 9s) during the divertor phase, only 8 discharges were run over the 10 hours of the session due to the time required for the tungsten tile to cool down in between discharges.

Independently of the plasma scenario, three phases can be distinguished in the discharges for comparison of JET-C and JET-ILW: the I_p/n_e Ramp up (in limiter phase leaning on Be), the plasma operation and heating phase on the divertor (tungsten PFCs) and finally the recovery by outgasing in between pulses. In the first phase, the gas consumption is higher in JET-ILW compared to JET-C $\sim1.0\times10^{22}$D in Be/W compared to 0.5×10^{22}D in C. However, this extra amount injected is recovered in the recovery phase between pulses with higher outgasing after the pulse [**9**]. On **figure 2** the amount of gas recovered as a function of the total amount injected is presented for the JET-C and JET-ILW configurations and it can be seen that the amount recovered with JET-ILW is somewhat larger that with the JET-C and al so that the global behaviors are similar. Indeed, the fraction recovered is always larger than the plasma content (1.5 to $3x10^{22}$D recovered compared to $0.5x10^{22}$D in the plasma), independent of the vessel inventory and no history effect is observed. Contrary to JET-C, no additional gas released after the disruption has been observed so far with the JET-ILW and identical breakdown afterwards is obtained. This significant improvement on the plasma restart after disruption is attributed to less gas in the wall compared to C [**10**]. Within a factor of ~2 the recovery with the JET-C and JET-ILW is in the range $1.5\text{-}3\times10^{22}$D demonstrating that the drop of the long term retention by a factor of about 10 can be attributed to the divertor phase and the plasma scenario. Indeed, for all the X-point phases and associated plasma scenario (from ohmic to type I ELMy H-mode) the gas consumption required for maintaining the same plasma density with the JET-ILW is significantly lower than with the JET-C. This is very good news since this part of the pulse is to be extended by a factor of 40 from JET-ILW to ITER. Indeed, since the short term retention is roughly compensated by the recovery by outgasing in between discharges, the drop of the long term retention observed during these experiment can be therefore attributed to a significant reduction of co-deposition (known to be proportional to discharge duration) and implantation (limited through saturation process). Also, and although the discharge duration in JET is not long enough for reaching steady state configuration, it is therefore not possible to fully separate the contribution of the long term and dynamic retention in the particle fluxes. However, the comparison of the resulting retention particle fluxes in between JET-C and JET-ILW exhibits a significant difference and it is presented and discussed below.

4. PARTICLE FLUXES

According to the first results of gas balance for long term retention analysis, the major gain on the long term retention is obtained during the divertor (X-point phase) and the heating phase (plasma scenario) where most of the fluence is obtained in the divertor. This is illustrated on **figure 3** showing the comparison of two discharges: Pulse No's: 72439 with JET-C and 81622 for the JET-ILW. The main parameters of these two discharges are $I_p/B_T = 2.0MA/2.4T$, with type III ELMy H-mode, constant gas injection of ~$6.0\times10^{21}Ds^{-1}$ from the divertor region and 5.0 MW of auxiliary heating. It is worth noting that for the JET-C pulse ICRH is used as main heating system whilst NBI is used for the JET-ILW pulse. However, from experimental results in carbon, when moving from L-mode to type I ELMy H-mode, the retention rate increase is only a factor of two showing that the correlation of the retention with the plasma scenario is modest and as a consequence consistent with the comparison presented here. On this figure, the retention particle flux is deduced from the global gas balance. The sum of the integrated pumped particle fluxes, during the plasma and in between discharge, is equal to the amount regenerated from the cryopump at the end of the session. The outgassed part in between pulses is evaluated by the neutral pressure in the torus and the resulting pumping speed of the cryopump in the torus calibrated through gas injection without plasma. Then, the pumped particle flux during the discharge is deduced from the cryopump pumping speed associated to the Baratron pressure type gauge located in the subdivertor. It is worth noting that the retention flux includes both the dynamic and the long term retention and that their respective contributions in the retention particle flux cannot be separated on the time scale of the plasma discharges run in JET. From **figure 4 (fig.3.e** expanded), it can be seen that at 56s for the JET-ILW pulse, although the plasma is in X-point phase on the W divertor, a significant retention of ~$1.0\times10^{21}Ds^{-1}$ still results with JET-ILW compared to about ~$3.0\times10^{21}Ds^{-1}$ with the JET-C. This is only a factor of 3, but it is very clear that if for JET-C the steady state is nearly reached, this is not the case at all for the JET-ILW which still exhibits a strong drop. On the base of the discharge duration (in the range of 10-15 s for JET), the transient phases have a significant impact on the reconstruction of the particle fluxes and the steady state level expected for co-deposition is difficult to assess. Indeed, as observed on the two curves for JET-C and JET-ILW, the contribution from the short term appears on the top of the long-term retention which represents the base of the particle flux and not reached over this time scale. However, from the time behavior of the retention fluxes (**figure 4**), an extrapolation leads to long term retention of about ~2.8×10^{21} Ds^{-1} for JET-C and ~$0.4\text{-}0.5\times10^{21}$ Ds^{-1} for the JET-ILW exhibiting a ratio of 7 in the particle flux retention. Such a ratio is consistent with the drop of 10 evaluated for the long term retention for the full divertor phase and evaluated through the gas balance (section 3).

In contrast to AUG [**8**], where both a steady state phase and an equilibrium are reached in between the particle injection and the particle exhaust (retention below 1%, the retention rate obtained during the X-point phase for the JET-ILW is significant although the plasma is in contact with the tungsten divertor. Compared to AUG, this residual retention can be attributed to the Be. This is supported by the comparison of the retention obtained during a limiter discharge (Be) and an X-point discharge (W) with 0.5MW of ICRH and exhibiting the same retention rate as shown on **figure 5**. For these two pulses, the PD was off and therefore for steady state plasma density conditions, the gas injection required for maintaining the plasma density constant is simply equals to the retention. In both cases (Be limiter and W divertor) the same gas injection (and therefore retention) of $\sim 5\times10^{20}$ Ds^{-1} is required for maintaining the plasma density constant. This behaviour supports the retention mechanisms based on erosion from first wall (Be), leading to codeposition in the divertor area through transport in the SOL.

Finally, it is worth noting that in addition to the overnight outgassing, a further drop of the retention could be observed over long term due to the regular drop of the residual carbon [**5**] all along the experimental campaign. Indeed, and as observed for the preliminary experiments on AUG when they moved to the full tungsten configuration [**8**], retention process due to residual carbon is very likely contributing to the overall long term retention. Post mortem analysis planned before the end of the year 2012 should confirm and consolidate the lower amount of D retained in the vessel and identify the location of the D codeposited with beryllium in the divertor area whilst it will also clarify the possible contribution of carbon in the deposits

5. EXTRAPOLATION TO ITER

From all these series of experiments, the evaluations of fuel retention, based on ion and CX flux to the wall and resulting in D implantation in PFCs, erosion from these PFCs and codeposition, the predictions from laboratory [**6**] the tritium limit (700g) for ITER in the all C configuration could be reached in ~ 40 full performance discharges without active cleaning . Based on the same predictions from laboratory data for a wall at 200°C, a drop of a factor of 50 could have been expected, but so far, for all the plasma scenarios assessed, the resulting retention has been reduced within a factor of 10. However, and as discussed before, this factor is deduced from gas balance over a full day of experiments and it represents the upper value of the long term retention since it does not include the overnight outgassing which is not negligible in the overall gas balance for the JET-ILW. Also, since there is still some carbon in the edge plasma [**1**], a possible contribution of this residual carbon in the retention through codeposition could be observed as already seen in AUG [**8**].

Future post mortem analysis will clarify the potential contribution of layers (Be and C) in the retention process.

CONCLUSIONS

Prior to shut down for changing from JET-C to JET-ILW (Tungsten divertor and beryllium first wall) series of experiments on fuel retention with JET-C have been carried out for building references and for comparison with the JET-ILW. Particular attention and calibration efforts have been carried out through cross calibration in between gas injection and gas recovery in order to assess long term fuel retention within accuracy in the range of 1%. Dedicated gas balance experiments with the JET-ILW for different plasma scenarios in limiter, Ohmic, L-mode, type III and I ELMy H-mode configuration have been performed with and without active pumping with the pumped divertor. For all these plasma scenario the long term retention exhibits a significant drop by a factor of about 10 mainly associated to the divertor and heating phase and therefore to the plasma scenario. As for carbon experiments, no significant trend of the retention rate can be correlated with respect to the plasma scenario. However, and although steady state not reached during heating phase, the trend for retention observed on the particle fluxes suggests even a lower retention for longer divertor duration. As expected, the retention mechanism based on erosion from main wall (Be), transport trough the SOL and codeposition in the divertor region appears to be consolidated. So far, further drop can be expected due to the gas balance method used for these experiments and which represents the upper value of the long term retention since no overnight outgassing is taken into account. Also, the residual carbon can likely contribute in an upper value for the retention. Finally, these results are consistent with predictions for ITER and compared to C, in Be/W the long term retention should drop by a factor larger than 10 when considering the long term outgassing and possible residual contribution of carbon.

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Pulse type	Carbon (Ds^{-1})	Be/W (Ds^{-1})
Limiter (inner) 0.5MW ICRH (Pulse No: 82626)		8.9×10^{19}
L-mode 0.8MW ICRH (Pulse No: 81282)	1.27×10^{21}	4.8×10^{19}
L-mode 0.5MW ICRH (No PD) (Pulse No: 81970)	1.5×10^{21}	1.5×10^{20}
Type III 0.5MW ICRH (Pulse No: 81624)	1.37×10^{21}	7.2×10^{19}
Type I 11MW NBI (Pulse No: 82626)	1.7×10^{21}	2.7×10^{20}

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Table 1: Summary of the series of pulses and comparison of the retention obtained with the JET-C and with the JET-ILW. All pulses have been run with the main plasma parameters of I_p/B_T=2.0MA/2.4T, over sessions of about 10 hours and 10 to 15 repetitive pulses with the divertor cryopump "ON" and 25 pulses with the divertor cryopump "OFF" (L-mode, No PD).

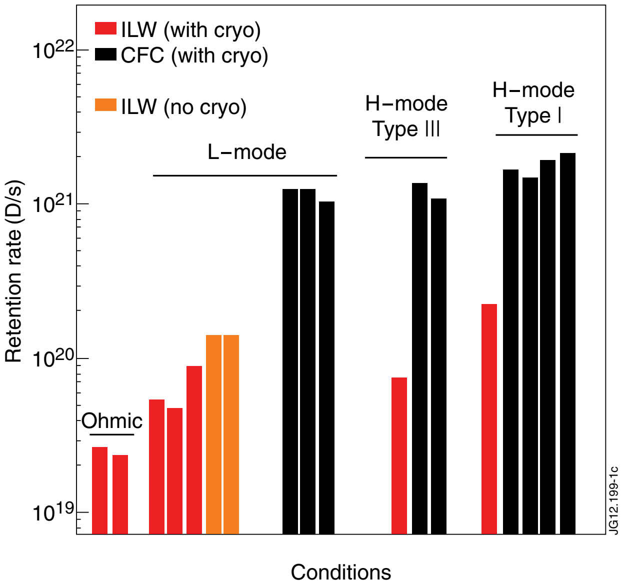

Figure 1: Fuel retention rates for different plasma scenario with Carbon and JET-ILW from gas balance normalized to divertor time. All the experiments were performed with the pumped divertor (with cryo) except the orange bars corresponding to experiments without active pumping (no cryo).

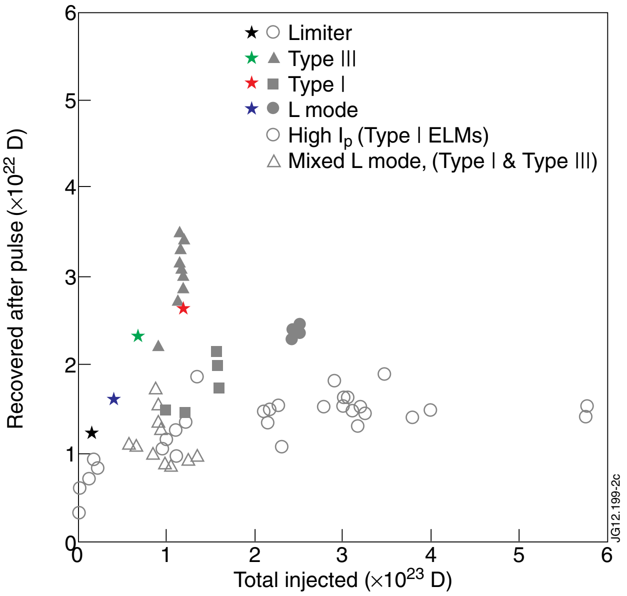

Figure 2: Particle recovery as a function of the total amount of particles injected for different plasma scenarios. The grey points correspond to JET-C experiments whilst the stars in colors represent the recent results from the JET-ILW.

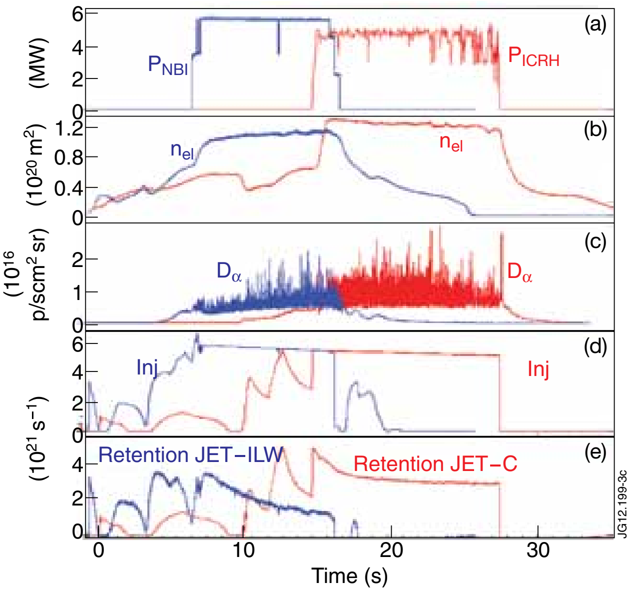

Figure 3:Comparison of a typical type III ELMy H-mode in JET-C and in JET-ILW configurations a) total auxiliary heating, b) plasma density, c) Da emission from the inner divertor, d) gas injection and e) resulting retention particle flux.

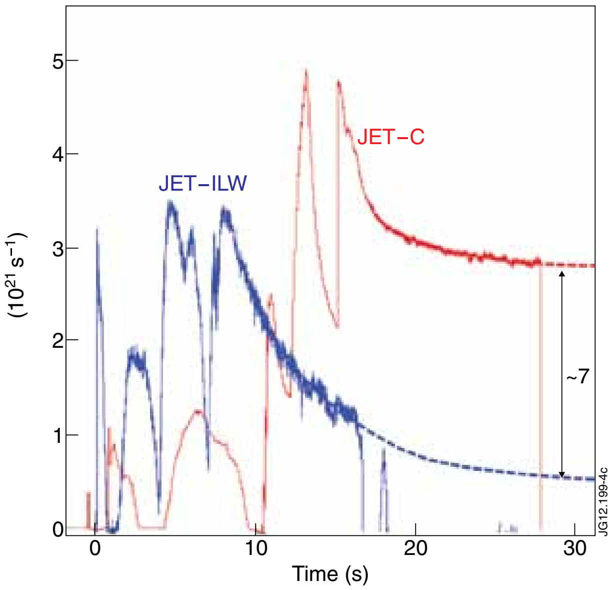

Figure 4: Retention particle flux (Dynamic and long term) for the two discharges presented on figure 3. The steady state is not reached at all particularly for the JET-ILW case and extrapolation of the particle flux suggest a ratio of at least 7 in between JET-C and JET-ILW.

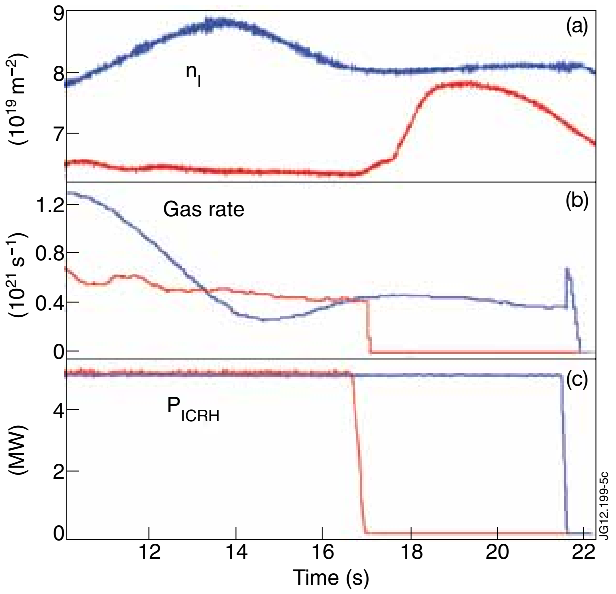

Figure 5: Comparison of the retention rate with the JET-ILW for a limiter pulse (Pulse No: 82626 red line) and an X-point divertor (Pulse No: 81790 blue line) showing the same retention flux, a) plasma density, b) gas rate and c) IRCH power. For these two discharges, there is no active pumping by the divertor cryopump and therefore, a direct evaluation of the retention flux can be obtained through the gas injection required for maintaining the plasma density constant during the steady state phase.