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ABSTRACT.
In order to achieve high accuracy gas balance and to minimise the contribution from previous experiments (history), fuel retention has been studied in JET in series of repetitive and identical discharges (6 to 8). The particle retention has been assessed for L and H-modes type I and type III (ELM energy up to 400kJ) ELMing H modes. The main parameter ranges of these discharges were I_p = 1.8-2.5MA, B_T = 1.8-2.7T, gas rate ~0.5 to 1.7×10^{22} Ds^{-1}, high triangularity and auxiliary heating from 2 to 18MW (ICRH and NBI) respectively for the L and type I ELMing H-mode. When averaged over the heating phase, the retained flux varies in the range of ~2.0~$\times 10^{22}$ Ds^{-1} for the L-mode to ~2.8×10^{22} Ds^{-1} for the Type I ELMs. Extrapolation to higher plasma performances (I_p = 3.5MA, 24MW of NBI+ICRH, gas injection 5×10^{22} Ds^{-1} and 9.5MJ of diamagnetic energy) using the same plasma shape exhibit retention as high as 3-4$\times 10^{22}$ Ds^{-1}. The particle recovery between discharges (in the absence of disruptions) is also shown to remain in the same range from pulse to pulse at around ~2-3$\times 10^{22}$ D and not correlation of the retention with the plasma performance has been identified.

1. INTRODUCTION

Fuel retention is one of the crucial points to be investigated for next step fusion devices in particular when using Plasma Facing Components (PFCs) of carbon and for the long discharges foreseen in ITER (400s ~ 7min). From the licensing limits for the operation of ITER, the maximum for the inventory of releasable tritium in the vacuum vessel is 700g [1]. Assuming an equal mix of deuterium and tritium, a fuel injection rate of 200 Pa.m^{3}s^{-1} (or 5×10^{22} Ds^{-1} at 293K) and a T retention of 20%, this limit would be reached in about 35 discharges without any dedicated cleaning efforts (1% of retention of the T injected in ITER leads to a retention of 1g of T per discharge independently of the material).

Although carbon will be very likely removed after the H-He phase, T retention constitutes an outstanding problem for ITER operation and also particularly with the material mixture since so far no experiments have been performed with this material configuration (Beryllium and Tungsten). The two main mechanisms for the long term fuel retention are identified as implantation and co-deposition [2, 3]. Deep implantation, diffusion/migration and trapping in the bulk material result from the direct interaction with the ion plasmas and/or the neutral from charge exchange fluxes. The co-deposition process results from the combination of both the recycling hydrogen flux and the sputtered atoms from the wall. These eroded atoms from the wall are ionised and transported through the SOL, recycle and arrive in several steps in the divertor region. Eventually, part of these carbon atoms are co-deposited with deuterium in shadowed area and forms flakes and/or layers.

The fuel retention resulting from these processes is generally evaluated by two complementary methods: the gas balance and the post mortem analysis. The gas balance provides information on “how much” retention occurs in a discharge, a day or even up to a week of experiments. This method is widely used in fusion devices [4] to evaluate the retention as a function of time resulting from the deuterium recycling flux and the impurity production e.g. by ELMs over a wide time scales in the 0.1 to 100s range. This method delivers a global measurement of the in-vessel inventory built up, based on the difference between the injection and the exhausted flux.

In JET a series of experiments have been performed whilst the machine is still in carbon. The objective is to build a reference data base of retention in the machine in carbon before moving to a full metallic wall with the ITER Like Wall (ILW) project with the first wall in Berylium and the divertor in tungsten. The reference discharges will be carried out in order to quantify the benefit in terms of retention in a carbon free device and compare to carbon. It is also worth noting that, as for carbon devices, post mortem analysis will be essential in Be/W to assess where the retention takes place and certainly also for guiding the development of efficient fuel removal methods and/or cleaning. Finally, some experiments with large ELM energy (>~0.5MJ), will not be possible in Be/W configuration and have to be performed before changing the facing components. These experiments will be used as a reference for scaling of fuel retention as a function of the plasma scenario.

2. EXPERIMENTS

A series of consecutive and repetitive discharges has been performed in JET L mode, Type I and Type III ELMing H modes with the following main parameters: $I_p = 1.8\text{-}2.5$MA, $B_T = 1.8\text{-}2.7$T, gas rate ~0.5 to 1.7×10^{22} Ds^{-1}, high triangularity and auxiliary heating from 2 to 18MW (ICRH and NBI) respectively for the L and type I ELMing H-mode For all the experiments, active pumping was ensured by the divertor cryopump only and its regeneration before and after (~at least 1/2 hour after the last pulse) the series of pulses thus allows a direct measure of the long term retention. The short term retention corresponds to the outgassing flux occurring between the discharges and is exhausted by the divertor cryopump. The accuracy of the active gas handling system used at JET for the analysis of the gas regenerated has been estimated to be better than ~1%. For the NBI heated shots (type I ELM experiments), the amount of gas pumped by the neutral beam ducts was evaluated from neutral pressure measurements during and in between shots with an in-situ calibration before the experiments. In all the series, the pulses were repetitive and reproducible plasma conditions were obtained in all the shots. There was no wall conditioning before the experiments neither (No He glow discharge cleaning, nor Berylium evaporation) and no disruption occurred in the session, except for the series of type I ELMy H-mode. However, the small extra amount recovered after this disruption (~3×10^{22}) compared to standard outgasing, shows that the contribution of this disruption in the gas balance is negligible and does not affect/modify the overall conclusion. One of the objectives of running repetitive discharge with the "same" plasma scenario is to avoid/limit the contribution of the history on the results. Although running repetitive pulses is time consuming, the impact on particle fluxes can be significant as illustrated on figure 1 showing the retention as a function of time for 8 consecutive and repetitive discharges with ELM control (Vertical kicks). For this series, the main plasma parameters were $I_p = 2.0$MA, $B_T = 2.4$T and 10MW of auxiliary heating

(9MW of NBI +1MW of IRCH). From this series of discharges, at least 2 to 3 pulses are required before reaching steady state conditions for the retention. Indeed, at t = 60s, drop of 25% between the 1st (0.6×10^{22} Ds^{-1}) and the 4th pulse (0.45×10^{22} Ds^{-1}) is observed. Conversely, negative retention is observed generally for the first pulses following modification of plasma scenario particularly when the locations of the strike points are changed.

3. RECYCLING FLUX AND RETENTION

The signal from horizontal, outer and inner divertor is difficult to exploit as they appear as a function of time since there are very transient as the ELMs occur (figure 2a). Also, when evaluating the retention, the time constant of the sub divertor pressure gauge used for the reconstruction of the overall pumped flux during the entire session is significantly longer (~300ms) than the ELM phenomenon (<0.5ms). As a consequence, integrating these signals over the heating period allows averaging the recycling flux as shown on figure 2b and the same signals integrated from 53 to 65s and assuming that no detachment occurs in the inner leg region (confirmed by Langmuir probes in the divertor). Similar behaviour for outer and horizontal views of the spectrometer is observed for these high triangularity discharges (so called HT3 and HT3_R configurations). All these discharges are Type I ELMy H-mode with I_p/B_T = 2.0-2.5MA/2.4-2.7T, a total input power of P_{tot} ~13-19MW, an ELM frequency from 15 to 100Hz and an ELM energy respectively in the range ~300 to 100 KJ. Finally the gas injection varies from ~0.6 to 1.7×10^{22} Ds^{-1}.

Over the heating phase, which also combines the gas injection phase, the integral of the D_α signal exhibits different slopes corresponding to the recycling flux averaged on the inner leg region. When plotting the retention over the averaged D_α signal phase a clear dependence of the retention with Da from the inner region results as shown on figure 3. For L and type III ELMy H-mode, the averaged recycling flux is lower than for type I ELMy H-mode. The negative retention points correspond to experiments with very small gas injection and always exhibit transient behaviours in the retention. Indeed, as soon as the Ip, input power or gas injection (recycling flux) are increased, the trend of the retention increases as well. The overall range of retention is around 0.2×10^{22} Ds^{-1} and a strong increase up to 0.65×10^{22} Ds^{-1} is then observed. This result corresponds to a pulse (Pulse No: 77992) with Ip=2.5MA, a total input power of 20.5MW (18.4MW of NBI + 2.1MW of ICRH) and a gas injection of 1.6×10^{22} Ds^{-1}. It is worth noting that no trend is observed with D_α signals from the outer leg and horizontal view. Extrapolation to higher plasma performances with same shape and attached plasma has been carried out for plasma discharges with I_p = 3.5MA, B_T = 3.2T, a total input power of 23MW (NBI+ICRH), gas injection of 5×10^{22} Ds^{-1}, ELM energy in the range of 600-700kJ (Pulse No: 69767). Using the same pumping speed associated to the sub divertor pressure retention as high as 3.8-4.0 $\times 10^{22}$ Ds^{-1} results which represent more than 75% of the injection. For these experiments it is difficult to evaluate the possible contribution from history effects since very few repetitive pulses are performed at this level of power. However, and although for these very high recycling fluxes the history contribution is certainly not negligible, such huge retention shows that for devices like ITER, in which the recycling flux will be larger than nearly 10, the resulting retention would be unacceptable for safety reasons and the limit of 700g in the device would reached in few pulses.

Finally, and although not shown here, for all the discharges studied in these series of fuel retention experiments, in the absence of disruption, within a factor of ~2, the recovery is constant and in the range of 1-3$\times 10^{22}$ D and independently of the plasma conditions; so far no clear trend with respect to the main plasma parameters have been identified [4].

CONCLUSIONS

Series of experiments of gas balance integrated over a session have been carried out on JET (one plasma scenario per session) allowing for a good accuracy (~1%) coupled with the active gas handling system of JET. Although time consuming, it is efficient for identifying possible effects/contributions from history effects. Reconstruction of particle flux (injection, pumped and therefore retention) over the full session (plasma and in between discharges) has permitted fuel retention analysis for different reference plasma configurations. Retentions in the range of 0.2 to 0.6×10^{22} Ds^{-1} have been deduced, representing a retention range of 20% of the gas injection. The general trend of the retention is to increase with the gas injection and the global recycling flux. Extrapolation of fuel retention for high performance plasma experiments with the same plasma shape has been carried out and retention as high as 3.8-4.0$\times 10^{22}$ Ds^{-1} have been deduced. All these experiments will be used as reference for comparison of the retention with the ILW project at JET and therefore for evaluating the benefit of moving to Be and W.

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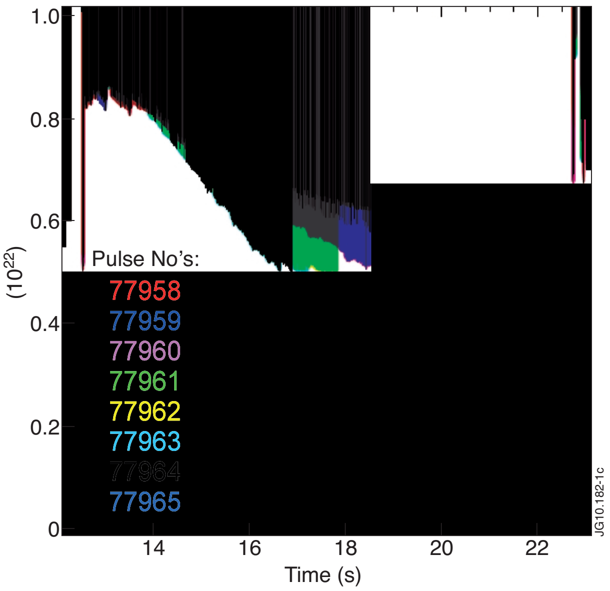

Figure 1: Retention as a function of time from pulse to pulse showing the history contribution on the retention for the first discharges of the series.

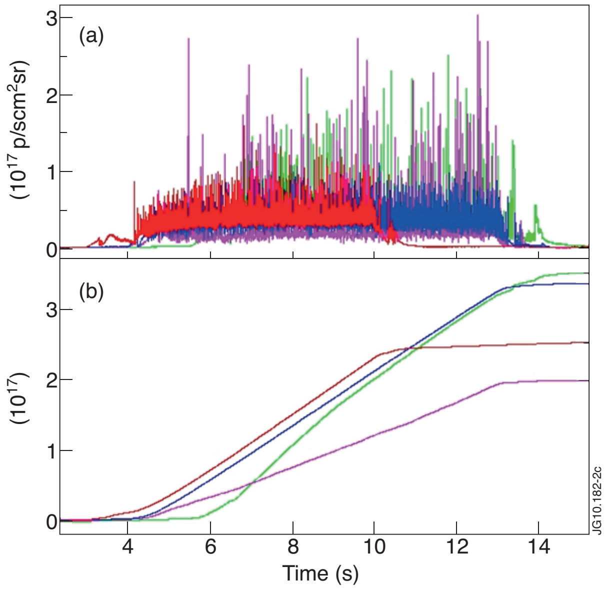

Figure 2: D_α signal from the inner part on the divertor for different plasma configuration for Pulse No's: 69260 (red), 76720 (blue), 76727 (pink) and 77992 (green)

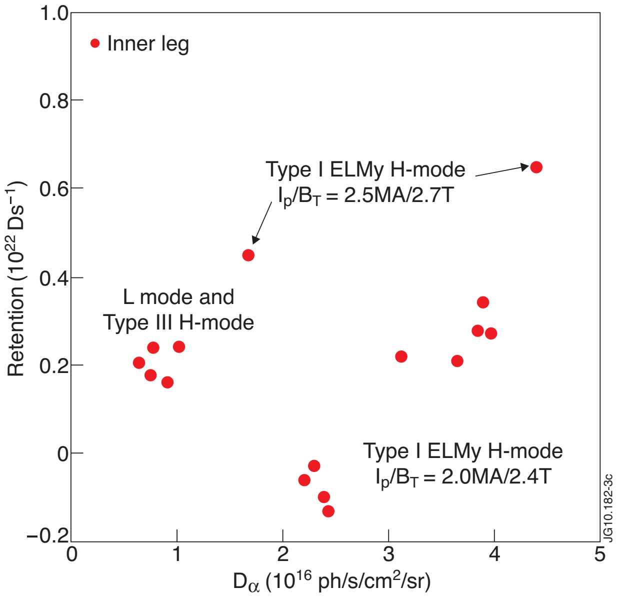

Figure 3: Retention as a function of the D_α signal from the inner leg of the divertor for different plasma shape and plasma scenario.