Dynamic Fuel Retention and Release under ITER-Like Wall Conditions in JET
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* See annex of F. Romanelli et al, “Overview of JET Results”, (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).
ABSTRACT
The dynamic retention of fuel and their subsequent release in between discharges has been analyzed under the new ITER-like wall conditions in JET. Limiter discharges are determined by plasma interaction with the Be walls and show a very reproducible dynamic wall retention and release with no significant memory effect of the loading conditions from previous discharges. The dynamic retention at the end of discharges reaches values up to ≈3 × 10^{22} D-atoms. The retention rate at the beginning of the density flat top is typically ≈5-10 × 10^{21} D/sec, with only a moderate decrease of few%/sec. Within the accuracy of the present pressure measurements at JET, the retained fuel during plasma operation is released in between discharges, in agreement with gas balance studies based on cryopump regenerations (1). The temporal behavior of the deuterium releases observed for about 1 day follows a t^{-0.7±0.1} dependence, very similar to observations under C wall conditions.

1. INTRODUCTION
The analysis and control of the long term T retention in the vessel of fusions devices is among the most critical questions for the further development of fusion energy. Previous analysis under full carbon wall conditions in JET and elsewhere have found a large long term fuel (T) retention which extrapolates to an unacceptable T retention in ITER (and future devices) for operation for some longer periods under full carbon wall conditions (2, 3, 4,). It should be noted that this conclusion is mainly based on experimental data under full carbon wall conditions and no operational data exist for a combination of full Be wall with a CFC divertor.

Analysis and understanding of the long term fuel retention under the ITER like Be wall and W divertor conditions, is a main goal of the ILW project. Systematic gas balance measurements under these conditions have been performed which show a drastically (>10) reduced overall long term retention when compared with similar conditions under full carbon wall conditions. These results will be presented in a separate contribution (1). This contribution focuses on the dynamic part of the fuel retention and the characteristic of fuel release after the discharges. Limiter discharges have been used to identify the retention behavior of the Be walls alone. In diverted discharges, the plasma interaction with the main Be wall decreases and occurs largely with solid W and W-coatings in the divertor (5), (6). Part of the W surfaces in the divertor are most probably covered with Be deposits with some amount of W, oxygen, and residual carbon (7), leading to a more complex situation for the interpretation of the fuel balance in diverted configurations. More details of these deposits will be obtained only from post mortem analysis in the future. Diverted plasma discharges with no cryopump operation have been used to exclude the strong influence of the divertor cryopump on the particle balance.

Previous studies on dynamic fuel retention under conditions with carbon walls alone and with Be limiters and Be evaporation in JET have been done in (8, 9, 10). In general an increase of fuel consumption with a simultaneously increase of fuel release after the discharges has been observed when Be was introduced in JET, in general accordance with the results presented here.
2. EXPERIMENTAL CONDITIONS

The analysis of the dynamic retention and release is based on the gas injection data, the plasma particle content and neutral pressure measurements in the main chamber and the subdivertor during and in between plasma discharges. The particle injection system in JET has been calibrated and has an accuracy of ±1% (1). Divertor pressures are measured by baratrons in the cryopump volume behind the entrance slit to the divertor. Main chamber pressures are measured by penning gauges at different locations. Particle release in between discharges is recorded by the divertor baratrons and the main chamber pennings. The pennings have a nonlinear recording with pressure and have been cross calibrated against the divertor baratron pressures in calibrated gas injections alone done regularly before each operational day. From this the “effective” pumping speeds in the main and divertor chamber have been deduced. Using these effective pumping speeds and baratron (higher pressures) and penning (lower pressures) measurements, the particle release in between discharges has quantified. Shot oriented pressure data after discharges have been used which are available for ≈13min. Particle release until the beginning of next shot has been extrapolated assuming a continuous release behavior as discussed in chapter 5.

3. DYNAMIC FUEL RETENTION IN BE WALLS IN LIMITER DISCHARGES.

Pure limiter discharges interact only with the Be walls and have been used to identify the dynamic retention and release behavior of the main Be wall. Figure 1 shows the typical behavior of the retention rate and the integral wall retention from a series of reproducible limiter shots. A characteristic feature of the new ILW is that the dynamic retention is very reproducible from shot to shot, with no strong memory effect of previous discharge conditions, as often observed under C wall conditions. Figure 2 shows the wall retention rate at the beginning of the flat top density and the gradient of the retention rate averaged over ≈ 5s for this series of discharges. The retention rate in the beginning of the density flat top is reproducible with 6-7×10^{20} D/sec with a gradient of ≈ 4×10^{19}/sec, about 6% / sec. No exhaustion of Be wall retention has been observed so far in all limiter shots, with a gradual decrease which varies between zero (no decrease for 15sec flat top time) and 10% /sec. Figure 3 shows the wall retention for the limiter shot database analyzed for the first 8 months of the ILW operation together with the pressure signals integrated up to about 12 min after the shot end. The maximal wall retention is about 3×10^{22} D-atoms, but the retention is far from saturation (see also chapter 3). Figure 4 shows the particle balance based on pressure measurements for this series of reproducible limiter shots, for which the integral gas release has also been determined by dedicated cryopump regeneration and gas analysis (1). The figure shows the injection and the particle release until 840sec and extrapolated until the beginning of the subsequent discharge, assuming a uniform release behavior with Q ∼ t^{-0.7} (see chapter 5). Within the data accuracy, the cumulative release agrees with the amount collected, which has a higher accuracy in JET (±1%). All dynamically stored deuterium is released and the averaged dynamic wall retention is ≈1.22×10^{22} D/shot.
4. DYNAMIC RETENTION IN DIVERTED DISCHARGES
Figure 5 shows an example of the retention in an L mode diverted plasma discharge (no cryopumping active). When the plasma moves to the divertor configuration, the dynamic wall retention shows a drop within few seconds and then levels off. Figure 6a plots the total retention in the limiter and divertor phase for this shot series, showing at first a drop in the divertor retention until it levels off. Again, the retained fuel is nearly completely released in between shots (dynamic retention), as shown in fig.6b, which shows also the amount of D regenerated from the cryopumps. The averaged release in between shots from pressure data is $1.85 \times 10^{22}$ /shot, with the difference ($2-3 \times 10^{21}$) to the retention at the end of the shots ($2-1 \times 10^{22}$) representing the “long term” retention. This value is in reasonable agreement with the cryopump regeneration, which however has a higher accuracy and are used as reference data.

The quantitative analysis of dynamic wall retention in diverted plasmas with active cryopumping suffers from the uncertainties of the effective pumping speed during plasma operation. Typically about 80% of the injected D is pumped by the cryopump and the remaining 20% of D dynamically by the walls. However, the evaluation of the particle exhaust by the cryopumps from the dynamic subdivertor pressure measurements has only an accuracy of ± 10%. This hampers the analysis of the wall pumping part within the overall particle sink.

5. DYNAMIC WALL PUMPING IN HIGH DENSITY DISCHARGES
High density limit shots or density excursions (11) give further insights in the dynamic fuel retention capability. Figure 7 shows an example of a density excursion in an a H-mode discharge, showing a large dynamic retention up to $\approx 1.3 \times 10^{23}$ D-atoms, which is already released during the discharge. The remaining fuel retained at the plasma end is $\approx 4 \times 10^{22}$ D/atoms and about double the release after the shot. This is due to uncertainties in the effective pumping speed in the divertor during running plasma operation, as mentioned above To get agreement, the effective divertor pumping speed during plasma operation must be increased by about 18% over that evaluated in gas injection (without plasma) only.

6. CHARACTERISTIC OF DEUTERIUM RELEASE AFTER PLASMA OPERATION
The temporal behaviour of the deuterium released after the plasma discharges gives important information on the retention characteristic. The particle source $Q = p s - dp/dt V$, with $p$ the pressure, $s$ the pumping speed and $V$ the JET volume, can best be expressed by a power law $Q \sim t^{-n}$ with $n = 0.75 \pm 0.1$. The same behavior is observed for C walls in JET and elsewhere (12). An example of the long term outgassing behavior of D2 molecules measured by a quadrupole mass spectrometer is shown in Fig.8. This behavior is followed here for about 1 day. It should be noted that a faster decay must occur at some time, since the continuous release of D with this temporal behavior would not converge. However a clear indication for this has not been found at present timescales observed.
6. DISCUSSION

The walls of fusion devices can store significant amount of hydrogenic fuel during plasma loading which is then released already during or in between discharges. In present short pulse devices as e.g. JET, the long term retention (which is the safety concern), is only a small part of this dynamically stored fuel and not correlated a priory with it. Dynamic retention is due to a temporally filling of regular or trap sites in bulk materials or codeposits which can be emptied in the course of hours, while “long term retention” occupies trap sites which are not emptied within this time scales. The data show also that the particle release is a continuous process and longer waiting times before cryopump regeneration would lead to larger release. In this sense, the transition from short to long term retention is not fixed.

The fuel retention of the Be walls (Be limiter discharges) show a pronounced dynamic wall retention which is stronger in the plasma built up phase, with values in the beginning of the flat top phase of ≈ 5-10×10^{21} D-atoms/sec. This retention rate decreases only slightly with time, typically 0-10% /sec. No saturation of the retention at the JET shot time scales has been observed. The total retention is ≈1.5-3×10^{22} D, but larger retention up to ×10^{23} D can be obtained during short time density excursions. Within the accuracy of the present measurements, the retained D is released in between discharges and the small long term retention part cannot clearly be resolved with this type of analysis.

A deeper discussion on the underlying physics of the observed dynamic retention behavior is not possible in the frame of this paper, due to the complexity of the physical retention mechanism and the more global observations available at the moment. The dynamic retention can be by D-implantation, subsequent diffusion, surface recombination and release in bulk Be or by release from Be- codeposited with fuel during plasma operation. Considering the latter case, the total amount of the Be source in the limiter configuration can be estimated to ≈ 4-8×10^{20} Be/sec (assuming similar physical sputter rate of Be than physical + chemical erosion of C), which, compared with a retention rate of ≈10^{21} /sec can hardly be (fully) responsible for the D-retention. This retention mechanism will also not exhaust with time but can contribute to the retention at the end of discharges when the dynamic trap sites are more and more occupied, which shows up by the decrease of the retention. The physics of implantation, diffusion and release in Be has been discussed in various previous papers (13, 9, 14, 8). The implantation of D-ions in bulk Be tiles is only 3-8nm, with some deeper penetration possible for higher energy charge exchange D-atoms. Distributing the retention at the shot end over 10m^2 (≈limiter area) or wall (≈100m^2) the areal retention density at the shot would be ≈10^{17} or 10^{16} D/cm^2 respectively, which would result in D/Be concentrations (0.2-2) if distributed over the implantation range of 5nm, which must be occupied and emptied in between shots. In accordance with previous conclusions, the amount of retention, the temporal behavior of release (12, 15) and data on the H-diffusion in Be (16) does not support a diffusion limited retention and release but require the dominance of surface recombination limited release and diffusion via trapping and release from trap sites, as e.g. described in (13). In order to match the amount of retention and the temporal release, the ratio D/K of the diffusion to the recombination coefficient must be about 1-2 10^{23}/m^2. With a
recombination determined release, the actual surface conditions of Be and thus possible Be surface oxidation can have an important influence.

With the plasma going to diverted conditions and interacting also with the W surfaces, an initial strong dynamic retention is observed which decay fast within few seconds. This behavior is consisting with filling up near surface trap sites in with a larger recombination value. Obviously, this retention tends to saturate faster, within 1-3sec of plasma loading. Also, the dynamic retention in Be walls contributes still in the diverted phase, but a clear separation of the Be and W contribution is not possible from this kind of data. It should be noted, that the JET W coatings show a larger long term fuel retention, probably due to enhanced trapping sites which can also contribute to a dynamic retention in the W coatings. (17).

As observed in many experiments, Be and W have reduced trap binding energies for hydrogen when compared which causes the reduced long term retention under ILW conditions. This does not disagree with the observation of enhanced dynamic retention but means the existence of more traps together with higher surface recombination barriers which leads to filling and emptying of trap sites shot by shot. A precise answer on the saturation of the dynamic trapping in Be is not possible from these data, but the temporal decays observed predict also a significant and sufficient dynamic wall pumping for the ITER wall limiter startup phase, for which no significant divertor pumping is present.

SUMMARY
The main Be wall in JET shows a very reproducible dynamic fuel retention which is about 2-2.5 larger than that of C walls ( on the fluencies observed in JET) and show a negligible memory effect from previous plasma loading conditions. The flat top retention rate is ≈10^{21} D/sec in the beginning with only a moderate temporal decrease of few % /sec. No saturation during JET discharges time has been observed. Typical shot end retention is 1.5-3×10^{22} with maximal retention during short term excursions above 1023 D atoms. This dynamic retention is sufficient to provide wall pumping in the start up phase of ITER.

In diverted plasma configuration and interaction of the plasma with the W divertor, initially a strong dynamic retention is observed which however decreases in few sec.

Within the accuracy of the long term pressure measurements in between JET discharges, the dynamically retained fuel is fully released after the shots. A reliable measurement of the small amount that is not released in these time scales is only possible on cryopump regeneration (1). The temporal release behavior of the hydrogen release from the walls shows a power law behavior of t^{−0.7 ±0.1}, similar as observed for C walls conditions.

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Figure 1: Example of the behavior of plasma density, wall retention and integrated D retention for a typical limiter shot.

Figure 2: Initial wall retention rate during the flat top density phase and gradient of it for a sequence of reproducible limiter discharges.
Figure 3: Integral deuterium injection versus particle release after discharge for all shots in limiter database. (until April 2012).

Figure 4: Cumulative particle injection (circles) and particle release from integrated pressure measurements for a series of reproducible limiter discharges. Triangles show release until end of data recording (~700 sec) and squares the amount extrapolated until beginning of next shot.

Figure 5: Density evolution, wall pumping rate and cumulative retention for an L mode divertor discharge (no divertor pumping active).

Figure 6: (a) Wall retention during limiter (solid circles) and divertor phase (solid squares) for the L mode divertor shot series. (b) Cumulative injection (circles), particle release until end of data acquisition (triangles) and extrapolated to the beginning of next shot for the series of L mode discharge (no cryopump active).
Figure 7: Density ramp under H mode conditions: a) plasma content, b) wall retention calculated from dynamic particle balance, c) subdivertor neutral pressure d) cumulative wall retention.

Figure 8: Log log plot of the temporal behavior of the $D_2$ outgasing rate (from mass spectrometer data).

Figure 9: No figure caption supplied.