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Gas Balance and Fuel Retention in Fusion Devices

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ABSTRACT:
The evaluation of hydrogenic retention in present tokamaks is of a crucial importance to estimate the expected tritium (T) vessel inventory in ITER, limited for safety considerations to 350g. In the frame of the European Task Force on Plasma Wall Interaction (EU TF PWI), efforts are underway to investigate the gas balance and fuel retention during discharges and compare with that from post-mortem tile analysis integrated over experimental campaigns. This paper summarizes the principal findings from coordinated studies on gas balance and fuel retention from a number of European tokamaks e.g. ASDEX-Upgrade (AUG), JET, TEXTOR and Tore Supra (TS). For most devices, the long-term retention fraction deduced from integrated particle balance is ~ 10-20 % and is larger than the ~3-4% deduced from post mortem analysis of PFCs. However, from the database available from tokamaks with carbon as main PFCs, the important conclusion is that T inventory limit could be reached in ITER within only ~ 100 discharges and could therefore seriously impact the device operation unless efficient T removal processes are developed.

1. INTRODUCTION

Global particle balance gives insight into the exchanges of particles between the wall and the plasma which is essential in order to understand the plasma density behaviour and control. In addition, it gives access to evaluation of the wall particle inventory in dependence on the plasma scenario, which is crucial for understanding the fuel retention mechanism and the extrapolation to ITER. The particle balance equation can be written as:

$$\int_0^t Q_{gas}\,dt + \int_0^t Q_{NBI}\,dt + \int_0^t Q_{pellet}\,dt = N + \int_0^t Vessel\,dt + \int_0^t Divertor\,dt + N_{Wall} \qquad (1)$$

where Q_{gas}, Q_{NBI} and Q_{pellet} are the particle injection rates associated respectively with gas puffing, neutral beam injection and pellet injection, N_e is the plasma fuel content, Vessel is the particle flux pumped by the pumping system of the vessel (including vessel turbo-pumps and neutral beam boxes), Divertor is the particle flux pumped by the pumps of the divertor (or limiter in the case of limiter machine) and N_{wall} is the amount of particle trapped or released by the wall since the start of the plasma at t = 0.

This equation is verified at any time during and between the pulses and, in principle, the only quantity not accessible to direct measurement is the relative variation of the wall inventory N_{wall}. This particle analysis can gives the global balance over the pulse duration and thus the wall retention during transient phases of the plasma density ramp up (dynamic retention) and for the different plasma scenarios (eg. Baseline, hybrid or advanced tokamak). The first part of the paper discusses the gas balance for a number of European tokamaks e.g. AUG, JET, TEXTOR and TS, showing that the wall loading depends strongly on the scenario and the pulse length in steady state operations. The contribution of out-gassing from non-actively cooled plasma facing components can be a strong limitation in the interpretation of the gas balance and for the identification of the different retention processes. Long-term retention analysis shows that the gas balance is a reliable method for particle retention but limited for analysis over duration of the order of the day. For longer term retention analysis (weeks/months) fuel retention analysis by gas balance is hampered by changing vessel conditions, particular events like disruptions, vessel conditioning by glow discharge cleaning. In contrary, post mortem tile & sample analysis after experimental campaigns is a reliable method to evaluate long term retention, averaged over many conditions and wall treatments. This method leads thus to a lower estimation for the retention mainly due to the impossibility to analyse the overall device and also to find all the flakes. Indeed, the fuel vessel inventory deduced from gas balance is generally higher by factors around 3 than the inventory derived from post-mortem analysis.

2. RETENTION DURING THE PULSE

Today, nearly all fusion devices, (including machines with only or large parts of metal walls like AUG), are dominated by carbon as main material released form the walls and impurity in the plasma. Common features with respect to hydrogenic retention are observed in these devices. A peak in the wall loading occurs at the beginning of the plasma as shown in figure 1 which displays the time evolution of the retention in long discharges in TS. After this a decreasing retention rate occurs with a typical characteristic time ranging from 1 to 100 sec. Shorter time scales are generally observed on divertor tokamaks, as observed on JET [1] and on AUG [2] while in limiter plasmas as on Tore Supra and TEXTOR this phase is always longer extending up to around 100sec on Tore Supra, as shown in figure 1. This phase is attributed to the implantation and adsorption of hydrogen in the near surface. The amount of particle loaded by the wall during this transient phase is material dependent as observed on JET when using beryllium and carbon limiters. The amount of particles to injected to approach a given plasma density was significantly higher (~ 3-4) with Berylium than with carbon PFCs [3]. However, at the end of the pulse the recovery was also enhanced by the same factor. This dynamic retention is reproducible when the same pulse is repeated and not influenced by the discharge history of the retention. Indeed, special wall treatments like Glow Discharge Cleaning (GDC) can change this reservoir but only in a transient way, not reproducible. This retention is thus independent from the plasma conditions such as the plasma current, the total input power, the heating scenario, the fuelling method and also the flat top duration (>6min in Tore Supra) but the associated inventory is recovered at the end of the pulse.

In contrary, the retention observed during the second phase depends on the plasma conditions. A constant retention rate is observed for long duration pulses in TS where the fraction of the injected gas which is retained and can be as high as 50 to 60%. For low absolute fuelling amounts, however, the retention is shown to be close to zero. This is illustrated for AUG in figure 2 where a significant retention is observed unless low fuelling rate are used. For injection lower than $\sim 3\times10^{22}$D, the recovery after the pulse is at least equivalent to the input. This is independent of the dominant heating (NBI or ICRH) with no significant influence by the W coverage increasing between 2003 and 2005 (45 to 80% of W coverage respectively).

In AUG, typically 75% of the injected gas is exhausted during and in between shots. Another 10% is pumped during long periods (nights/weekends) leading to an estimated retention deduced from gas balance of 10 to 20%. The wall acts as an important dynamic particle sink/source; in high density discharges D is stored in the wall and for low density discharges the wall is depleted and the net vessel inventory can be decreased.

It is also worth noting that no influence of ELMs has been observed up to now on the global particle balance. However, the carbon transport at the edge is known to be significantly dependent of the power deposition and particularly during transient events like ELMs. Indeed, further analysis of Quartz Microbalance Data (QMB) mounted in the inner divertor louvre region in JET confirms that the carbon deposition is significantly higher for H-modes than L-modes. Also, plasma configuration is the most important factor determining the local material deposition at the QMB the difference between H and L mode being less pronounced with the strike-points are located on the vertical tiles. The largest deposition (up to $\sim 5\times10^{16}$ C atoms/cm^{2}s) occurs in ELMy H mode shots on the inner divertor QMB if the strike-point is located on the inner base tile with line of sight to the QMB [4]. This indicates that the local enhancement of the erosion/re-deposition does not contribute much to the global retention.

For short pulse duration the particle balance is dominated by the dynamic retention and the main processes that contribute to particle retention (shallow and deep implantation, co-deposition, diffusion) are difficult to separate under those conditions [5]. Long pulse operations in TS, indicate that the retention mechanisms are not only determined by co-deposition but also possibly by diffusion in carbon porosities. This is supported by analysis of carbon deposits originating from different locations inside the vessel revealing relatively low deuterium content, unable to account for the large deuterium in-vessel retention worked out from particle balance analysis [6]. Recent laboratory [7] data on deep penetration of hydrogen in CFC support this but more work is needed for a definitive conclusion. In TS, data indicate a strong dependence of the retention rate on the LHCD power as shown in figure 3 [8]. This effect is not observed for ICRH heating independently of the ICRH heating conditions. This is the only significant dependence observed on retention and no dependence from the fuelling method (pellets, gas injection) and radiation fraction has been observed up to now. A possible explanation could be the enhancement of the retention rate by a modification of the SOL induced by the supra-thermal electrons generated in front of the LH grill [8]. So far, a dependence of the retention on the LH input power has not been observed on other machines using LHCD as heating systems like JET and JT-60U.

In the second phase of the pulse for the non-actively cooled devices, “wall saturation” is reported when the increase in PFC temperature during the shot turns the wall from a net sink to a net source. This is observed in JT60U, where “wall saturation” does not occur in short pulses (< 15s), but appears progressively in repetitive long discharge [4]. This behaviour was also observed for repetitive discharges in TS before the CIEL upgrade where even moderate temperature increase of $\sim 20^{o}$C on non actively cooled area has been shown to result in an uncontrolled increase of the density. This shows that with non-actively cooled PFCs, the thermal out-gassing flux becomes non negligible for long discharges. When the out-gassed flux exceeds the total exhaust capability, density control is also lost in JT-60U in spite of active pumping by the divertor cryopump. In any case, this strong out-gassing does not prevent retention occurring in areas not directly heated/viewed by the plasma (first wall, gaps, below the divertorÖ). The so-called "wall saturation" is in fact a paradox in term of global particle balance since the strong heating of the target plates results in a "non-saturated" target plates, but only for these PFCs. It is worth noting that out-gassing is no more observed in "fully" actively cooled devices (Tore Supra) as shown on fig.1. The out-gassing source is controlled/constant, the retention rate is constant and no "history effect" for the same plasma parameters is observed.

The outgassed flux during and particularly after the pulse is of a significant contribution for the overall gas balance associated to short pulse duration. As shown on figure 4, after non-disruptive discharges the total recovery of D integrated 600 sec after the end of the shot as a function of the total D injected during the pulse for series of JET pulses with MKII-SRP and MKII-HD divertors. This amount does not vary significantly with the divertor type and is always larger than the plasma content ($2\text{-}6\times10^{21}$D), showing that the wall does trap and release particles transiently. The amount of particles recovered after the end of the pulse does not depend strongly on the discharge characteristics such as the fuelling method, plasma current, flat top duration, power input, heating scenario or plasma configuration: the amount of D released after a non-disruptive discharge is largely independent of the discharge history (see fig. 4). The same behaviour is found in AUG based on the D recovery by He GDC after the discharge [2] and in TS [5] with fully actively cooled PFCs.

The retention fraction is low for short pulses, while it is equivalent to the retained fraction during the pulse for long discharges, where the recovery after the shot becomes negligible compared to the wall inventory cumulated during the shot. This is clearly evidenced when performing particle balance integrated over longer periods (~ 10 hours) as shown on figure 5 which compares particle balance performed for a series of short pulses (~ 550s of cumulated plasma time in 24 discharges) and a series of long pulses (~ 1330 s of cumulated plasma time in "only" 7 discharges) on TS. For short pulses, the inventory cumulated over the day can be recovered by a night of He glow discharge cleaning ($\sim5\times10^{22}$D), yielding an overall balance close to equilibrium for short pulses as shown by the "blue" area at the bottom of figure 5. In contrast, long pulses lead to a significant inventory build up which is proportional to the discharge duration and which becomes much larger than the possibility of overnight He GDC recovery. Finally, for both series the contribution of the recovery in the overall balance is nearly the same (contributions of out-gassing for series of long and short discharges cannot be easily distinguished on fig.5) and becomes negligible in the overall balance. Accuracy in gas balance studies is however limited by the requirement to subtract large numbers when integrated over durations as long as days and even weeks of operation (pulse~10-20 sec compared to a day $\sim10^{5}$sec). The gas balance accuracy strongly depends therefore on the duration for the integration and particularly on the difficulty to assess the overall contribution of the hydrocarbons during plasma discharges, after disruption and particularly between discharges.

3. SAMPLE ANALYSIS IN AUG, JET AND TORE SUPRA

For long term retention integrated over an experimental campaign, post-mortem analysis is a proven method to assess the retention, however integrated over a full experimental campaign including various events: different plasma scenarios, conditioning procedures, disruptions. This method is commonly used in almost all the machines working on the long term retention. In JET, divertor tile analysis after the MkIIGB divertor campaign (total duration in divertor configuration of 57500sec (~16h00 of plasma) [9] found a C deposition of about 400g in the inner divertor mainly. During these plasmas a total amount of 766g of D has been injected corresponding to an integrated ion flux on the inner target of 1.3×10^{27}. This leads to a retention rate of 3.4×10^{20} C/s. In the deposits in the inner divertor the D/C ratio was as high as 0.2 and the overall D retention estimated from these data is about 4% (34g) of the total amount injected. However, samples from the divertor only have been included in this analysis. Neither tile gaps, nor inner wall guard limiters have been taken into account in this balance. This retention fraction of 4% represents thus a lower limit to the overall retention.

Recent analysis of tiles from the MKII-SRP divertor in JET show that the total integrated fuel (deuterium retention) in the divertor co-deposited layers is estimated to about 42g D compared with an integrated fuel injection of 1800gD yielding a retention fraction of 2.7 %, similar as observed in previous campaigns. This number represents a lower limit since it does not include retention in the main chamber, the private flux region tile (still to be analysed), tile gaps and so on. However, based on previous data, the additional retention expected from those areas is not expected to increase the present value by more than 50%, yielding an overall long term D retention of about 4% in the previous JET operation campaign.

Careful sample analysis has also been carried out in AUG to study the deposition of D, B and C in order to assess the effect of increasing coverage with W in AUG [9]. Coated divertor tiles (150nm of Re and 3μm of C) have been analyzed before and after plasma exposure using RBS and NRA. A total of 2.4g of D has been collected from the inner and outer divertor but also from below the divertor and behind the wall. This corresponds to 3.1% of the D input. This amount can be increased to 3.1g (4.1%) when assuming the same D/(B+C) ratio of 0.4 on the two vertical targets of the inner divertor. Optical inspection indicates that retention in tile gaps is probably small. For the 2002/2003 campaign, AUG was mainly a carbon machine with a retention governed by trapping on the inner divertor tiles, where 70% of the trapped inventory was found. 20% were found in remote areas (below roof, baffle,...). An overall retention of ~4% of the total input results, compared to 10 to 20% compared from gas balance analysis.

The 2004/2005 campaign, during the transition period to a full W machine (divertor and some limiters were still carbon) did not exhibit a significant difference in the retention compared to 2002/2003. During the 1995/1996 campaign of AUG, with carbon in the main chamber and W in the divertor, a retention of 2% of input has been estimated from sample analysis [10], close to the recent values.

In Tore Supra, gas balance integrated over a full campaign shows that ~25% of the injected gas is retained while only 3% was found in the deposited layers analysed so far [6]. This analysis has been carried out on deposited carbon layers removed from leading edges, of neutralizer, underside of the toroidal limiter, lateral faces of the antenna protection and from the outboard limiter. The D/C ratio observed in these layers is typically lower then 10% and the integrated retention in these layers counts for only 10% of the retained D in Tore Supra. A possible candidate for the retention is carbon deposited in the gaps between the fingers of the limiter and possible flakes below the limiter. Finally, as suggested by the constant retention rate during the long pulse operations and the dependence on LHCD bulk diffusion into porous CFC could also play a role. Indeed, laboratory experiments have evidenced a deep penetration of D into CFC, far beyond the ion implantation range. The retained fraction does not saturate as is the case with graphite, but increases as $(\text{fluence})^{0.5}$ [7]. However and up to now, in spite of efforts engaged in TS the particle balance cannot be closed yet.

DISCUSSION

For various devices, the long term retention fraction evaluated from integrated gas balance (~10-20%) is larger than the retention deduced from post mortem analysis of PFCs. which is ~3-4%. However both these methods are subject to large error bars. The D/T vessel inventory deduced from gas is generally higher by factors 3 to 8 than the D/T inventory that derived from post-mortem analysis of samples. With gas balance, it is difficult to determine the contributions over a full experimental campaign, from D recovery from wall conditioning, disruptions or out-gassing over long periods (compared to plasma operation).

For gas balance performed typically for an experimental day or week, the accuracy depends on the integrated difference between the injection and the exhaust. The contribution of non hydrogenic species (such as hydrocarbons) is another difficulty. In contrast, post-mortem analysis tends to underestimate the long-term retention since it can only be performed for a restricted set of samples, extrapolated to the whole device assuming toroidal symmetry, and has difficulties to account for all retention areas such as limiters and other large areas in main chamber, retention in gaps in between tiles etc. In AUG, the long-term retention deduced from the gas balance is 10-20 % of the injected particles, while it is estimated to be only 3% from post mortem analysis. In JET, post-mortem analysis also yields about a 4% retention rate, but gas balance integrated over experimental campaigns indicates retention of 6%, with no noticeable influence of the wall temperature (320 or 200∞C). During the DT experiments in TFTR [12] and in JET (1997-1998) [13], the immediate T retention has been shown to be about 40% during the campaign, while 17% (6g T) remained after intensive cleaning procedures executed after the D-T experiments in JET. Only 3g were recovered in the sample analysis, suggesting that the missing 3g would be found in flakes located in the sub-divertor volume in an estimated total amount of 1kg of flakes [14]. This shows that values deduced from post-mortem analysis tend to underestimate the retention mainly due to the impossibility to analyse the overall device and also to find all the flakes.

Assuming similar retention fractions in ITER as in the present carbon dominated devices, an averaged retention of 10 % and assuming a gas puff rate of $200 Pam^3s^{-1}$ for 50-50 % of D-T, ($5\times10^{22}Ts^{-1}$) yields an equivalent long term retention of 10g of T per 400 s discharge, limiting the number of shots to 35 before reaching the safety limit of 350 g, while a retention of 3% would increase this number to 115. The current selection of ITER materials (C, W and Be) should lead to a somewhat lower inventory compared to a full C machine, as most of the retention processes identified so far are linked to carbon (implantation of D in C, deep diffusion and trapping of D in C, codeposition of D with eroded C). However, there is presently no experimental data from tokamaks with the contemplated ITER material mix to assess this effect, and modelling is still at the early stage: large uncertainties remain on the predicted T retention rates.

CONCLUSION

Gas balance and fuel retention analysis carried out in AUG, JET, TEXTOR and TS, show that the wall loading depends strongly on the scenario and the pulse length in steady state operations. For longer term retention analysis (weeks/months) fuel retention analysis by gas balance is hampered by changing vessel conditions, particular events like disruptions, vessel conditioning by glow discharge cleaning. However, gas balance is one of the few possibilities to evaluate the fuel retention in ITER in the non-activated phase. Post mortem tile & sample analysis after experimental campaigns is a complementary method to evaluate long term retention, averaged over many conditions and wall treatments but performed for a restricted area. The resulting long-term retention fraction coming from integrated particle balance is ~ 10-20 % and is larger than the values of ~3-4% deduced from post mortem analysis of PFCs. Also, up to now, no significant influence by the W coverage increasing (45 to 80% of W coverage in AUG) and no influence of ELMs have been observed in the global balance. Finally, from the database available from tokamaks with carbon as main PFCs, the important conclusion is that T inventory limit could be reached in ITER assuming a similar retention then in carbon dominated devices within only ~ 100 discharges and could therefore seriously impact the device operation unless efficient T removal processes are developed.

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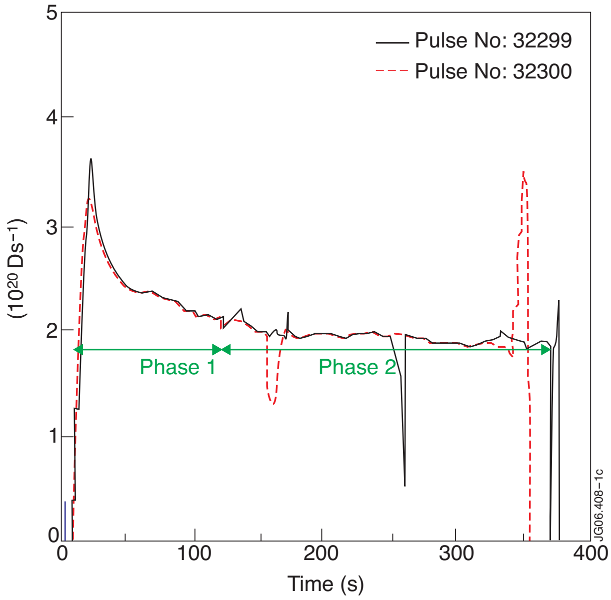

Figure 1: Retention as a function of time for long pulse operation in Tore Supra.

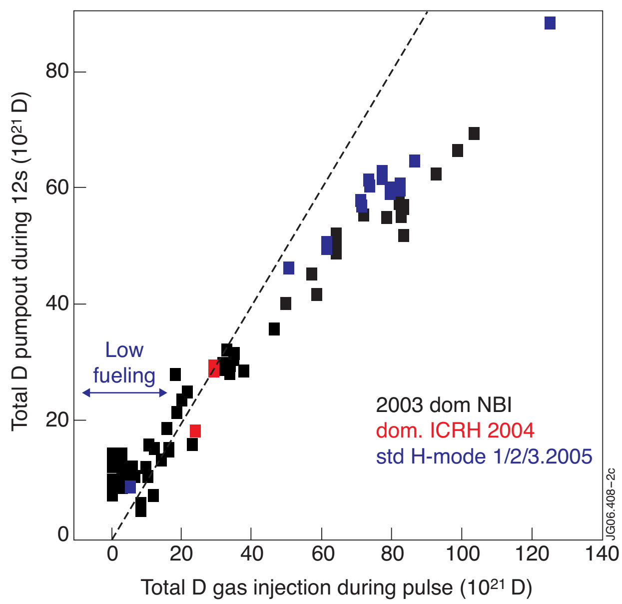

Figure 2: Particle recovery as function of total D injected in AUG. Different plasma scenario are reported and different W coverage.

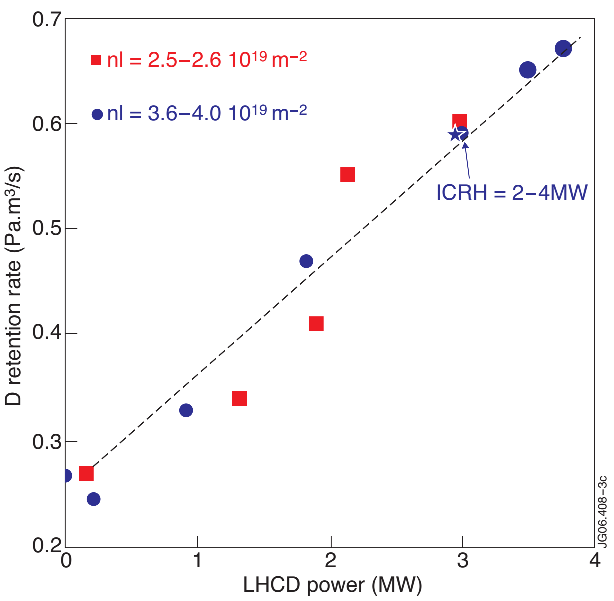

Figure 3: D retention rate as a function of LHCD power for different plasma densities and ICRH power in Tore Supra [6].

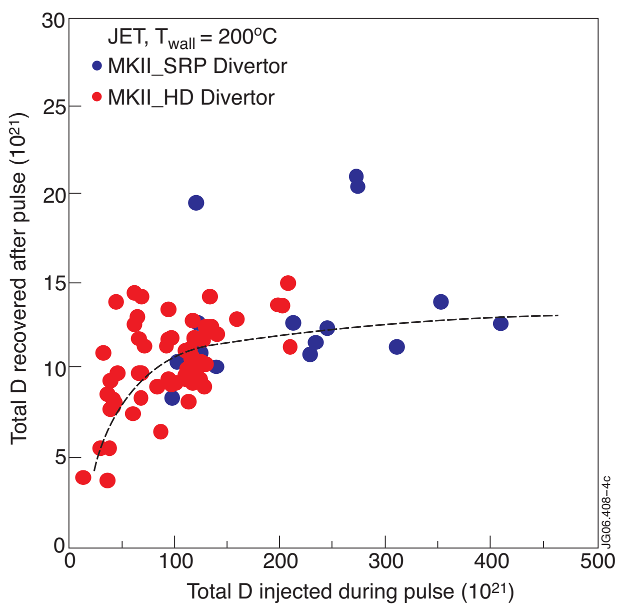

Figure 4: Total D recovered 600 sec after the end of the pulse as a function of the total D injected during the pulse for series of JET pulses with MKII-SRP and MKII-HD divertors

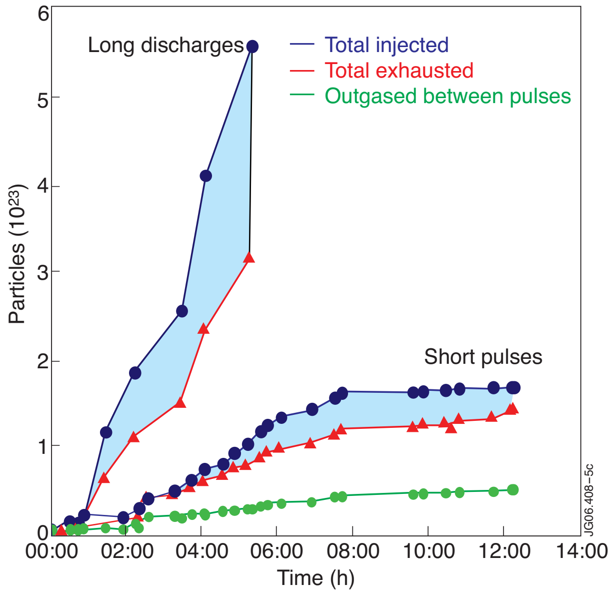

Figure 5: Integrated gas balance for a series of short pulses and for a series of long discharges. The outgased flux is plotted for the two series of experiments and exhibits the same trend.

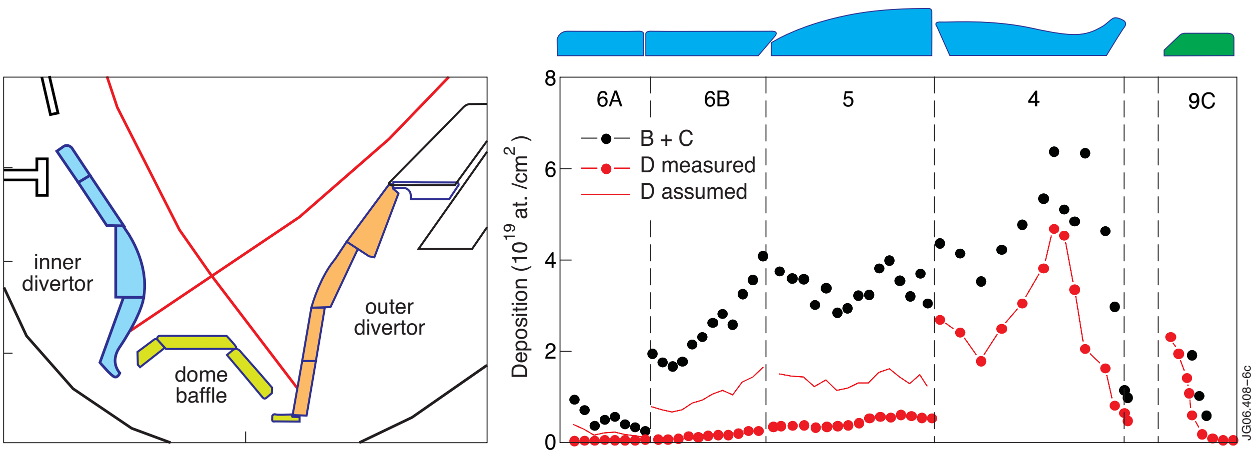

Figure 6: Deposition of D and C on the inner divertor of AUG for the 2002/2003 campaign [8].