Dynamic wall loads measured by gas balance technique in all tungsten ASDEX Upgrade

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Abstract New gas balance measurements in full tungsten ASDEX Upgrade are presented. Operation without active pumping yields an absolute retention of $10 * 10^{20}$ at D, in line with ALCATOR C-mod measurements. The outgassing could be by 3 exponential functions,which may be attributed to the behavior of neutral gas and the release of D from regions with different wall temperature. In 2009 longer discharges could be performed, which confirm the wall saturation observed in experiments at AUG. A clear dependence of the wall saturation on the amount of gas puffed not on the puffing rate is shown. The influence of boron layers on wall retention was investigated in detail.

1. Introduction

In vessel tritium inventory is still a safety issue for ITER. To estimate the amount of T retained in a future fusion device, measurements on present devices are needed. Whereas up to recently most ITER relevant divertor tokamaks operate with carbon plasma facing components (PFCs), high Z materials are only investigated in Alcator C-mod and ASDEX Upgrade (AUG) [1]. During the last years it was demonstrated that the long term retention of D in AUG is strongly reduced during the step by step transition from carbon to full tungsten PFCs [2]. Unfortunately post mortem analysis yield no time resolved information, which is desired to verify predictions to ITER. Gas balance measurements may fill this gap [3]. Investigating the time dependent behavior of the retention of different plasma scenarios allow identifying the mechanisms relevant for retention. Whereas the retention of hydrogen in a surface depends on the total fluency, chemical processes and deep implantation are expected to be constant. Unfortunately the fluency expected during an ITER discharge can not be achieved in present devices.

In this contribution we will present the latest results after a careful calibration of the gas inlet and pumping systems. Especially the pumping speed of the in vessel cryo pump determines the error-bars of the measurements. As the pumping speed of the cryo pump is limited by the conductance of the divertor slits and possible parasitic pumping from the midplane, the effective pumping speed has to be determined using real plasma discharges. To provide this calibration a series if discharges were performed at AUG. After these discharges, wall valves were closed, the cryo pump was warmed up and the in vessel pressure yield the integrated amount of gas pumped. Assuming a linear increase of the pumping speed with the divertor pressure, as expected for the divertor conductance in the pressure transition region, a simple fit was used to get the effective pumping speed of the cryo pumping system [4,5,6].

After the transition to full tungsten PFCs gas balance measurements are compared with the long term deposition determined using marker tiles. For W PFCs the long term retention is below a few percent of the amount of gas puffed within the error of a few percent [5]. This value is consistent with post mortem deposition measurements by ion beam techniques and thermal desorption spectroscopy [7]. However, as the amount of deposited D found on marker tiles is as low as 0.6 % of the total D inlet, the accuracy of the gas balance measurements was not sufficient for a quantitative comparison. Nevertheless gas balance measurements yield time resolved information, they are indispensable to extrapolate from 5 s discharges to long term ones. The typical behavior of the D retention is shown in Fig. 6. From the view of gas balances high density H-mode discharges could be divided into 4 different phases [5]. First, after plasma start up, the PFCs strongly retain D, until the wall is loaded. Only a small fraction of the puffed gas is needed to build up the plasma density. During the second phase, stable plasma conditions are reached. To maintain the plasma density, the gas flux can be permanently reduced or if the gas puff is constant, the divertor density rises, until the puffed and pumped gas are similar. This phase is transient, i.e. the D-retention is changing all the time. If the amount of gas puffed is high enough, the third, steady state phase is reached. Now a equilibrium of puffed and pumped gas is established. For typical AUG discharges the differences of the huge amounts of puffed and pumped gas is zero within the error bars of the measurements, which are a few percent. To reach this phase a typical inventory of $2 * 10^{22}$ at D has to be built up. It is not clear, if this inventory is retained only at the divertor, where the ion flux is highest or whether one has also to take the main chamber into account. Using the geometrical surface of the vessel as active surface this amount of D would equal 42 mono-layers on all surfaces. The last phase is characterized by outgassing, i.e. reduction of the D-content. This phase starts immediately when the gas puffing rate is reduced or the discharge ends. Obviously the in-vessel D inventory is dominated by dynamic wall loads.

To compare gas balance measurements one has to look carefully on the kind of measurements. The most straight forward way is to integrate a whole discharge, but for AUG there is a strong outgassing after the discharge. So the result will depend on the time, where the integration stops. For normal plasma operation, the integration is limited by the next discharge or other operations as for example calibration gas puffs and wall conditioning glow discharges. In summary for extrapolation to long term discharges, one has to take to the different phases of a discharge into account. The dynamic retention during plasma start up can be neglected and the steady state phase dominates the gas balance.

2. Discharges without pumping

Up to now gas balance measurements at AUG were focused on typical H-mode discharges [5,7]. The dynamic measurements allow to distinguish different phases of a plasma discharge, but the accuracy is limited to a few percent mostly by the determination of the amount of gas pumped. To get rid of this problem, ’static gas balance measurements’ were used in Alcator C-mod [8]. All valves to the pumping system are closed during the discharge and the vacuum vessel is used as storage. From the pressure typically 300 s after a discharge and the known amount of the gas inlet, in principle the wall retention could be determined. In C-mod the accuracy of this method is only limited by the volume measurement and the accuracy of the used capacitative gauges.

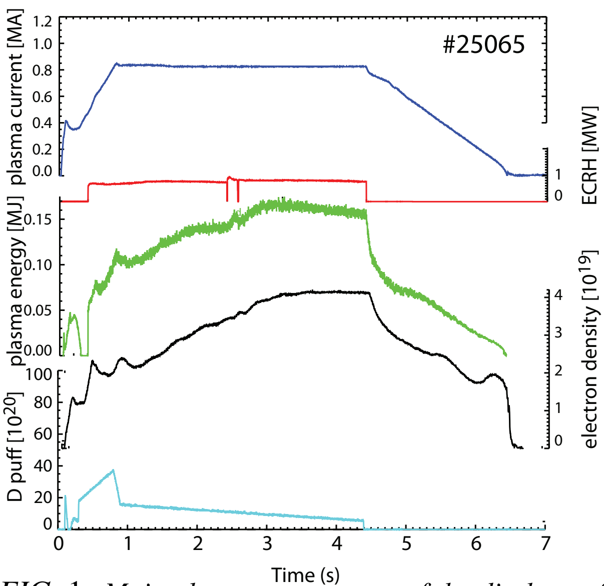

FIG. 1: *Main plasma parameters of the discharge 25065. From top to bottom are shown the plasma current, ECRH heating power, stored energy, electron density and the gas puff rate.*

From so called ’fizzle’ discharges the accuracy for these measurements was determined to $3.5 * 10^{19}$ D-atoms or for a typical discharge around 1 %. These kind of discharges show a retention of typical $10 * 10^{20}$ D atoms, or normalized to the amount of puffed gas up to 60 %. In order to measure the retained gas as accurate as possible, similar discharges without pumping were performed in AUG. The in-vessel cryo pump was heated up to liquid nitrogen temperature.

The main heating system at AUG are the NBI boxes, which could not be used as they act as significant pumping system, as soon as the local pressure at the midplane rises, i.e. after the discharges. The operation of the ICRH system, which delivers up to 6 MW in former times is strongly hampered by the radiation of tungsten eroded from the ICRH protection limiters due to shield rectification of the applied power [9]. Therefore only ECRH could be used, which delivers up to 900 kW for 4 s beside the ohmic heating. Typical plasma parameters of these discharges are shown in Fig. 1. They are stable ELM free H-mode ones, with $n_e \leq 4 * 10^{19} m^{-3}$ quite low for AUG. One has to keep in mind that for this kind of discharges a factor of 20 less gas is used than for typical H-mode discharges as discussed before [5,6]. The average gas input was set to $5 * 10^{20}$ and $10 * 10^{20}$ at/s. The discharge was ramped down slowly to avoid disruptions, which may influence the wall inventory, although no significant influence of disruptions on the gas release is observed in AUG.

To study the influence of wall loading by preceding discharges the investigations were performed twice. First during an operational day at the end of a week and again as first discharges of a week. The plasma parameters of the used discharge are shown in Fig. 1, and typical time traces of two calibrated capacitative pressure gauges are shown in Fig. 2 a. The measurement at the midplane shows a very low pressure during the discharge, whereas the divertor gauge shows a rising pressure. In Fig. 2 b the gas puff rate, the neutral gas inventory at the divertor and the midplane and the plasma inventory are summarized. To get stable discharge conditions, the gas-puff had to be reduced during the shot, nevertheless the neutral and plasma inventory are continuously rising, reaching no steady state phase. These data were used to calculate the amount of gas retained using:

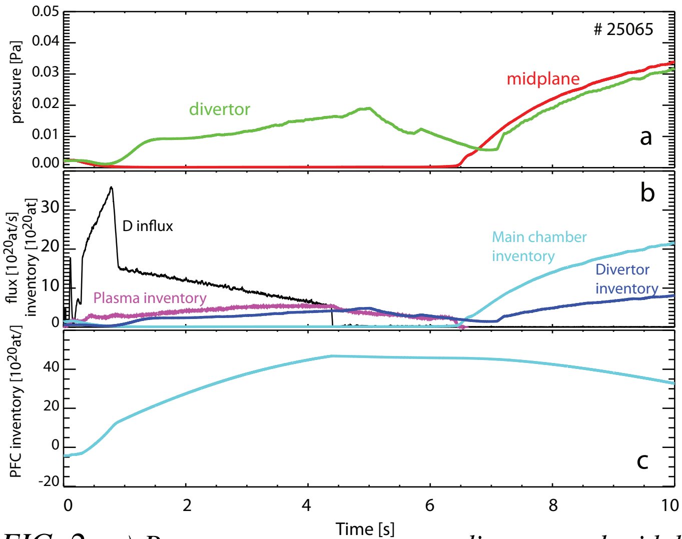

FIG. 2: a) Pressure measurements at divertor and midplane b) gas puff rate and inventories, c) calculated retention.

$$N_{wall} = (N_{pl} + N_{nt}) - \int \Phi_{valves} dt \qquad (1)$$

with N_{wall}, N_{pl}, N_{nt} the wall, the plasma and neutral gas inventory and Φ_{valves} the gas input by the gas valves. At break down, respectively, the wall inventory is first decreasing and than rising during plasma build up. During this time most of the gas puffed is pumped by the wall and the retention rate decreases during the discharge. At the end of the gas puff the wall inventory decreases slowly and the outgassing gets stronger after the termination of the plasma. Even for this low density discharge the dynamic pumping of the wall dominates and the outgassing has to be investigated carefully.

After the discharge the vessel pressure inventory is continuously rising, but in contrast to C-mod, no saturation was observed. For the data acquisition two systems are used. One records only the discharge until 28 s after the plasma breakdown with a high temporal resolution. The second diagnostic uses the same gauge but the data are recorded for 700 s with a lower time resolution of 6 data-points each second. The high resolution data were used to fit two exponentials with fast decay time. The first one leads to a time constant of 1.1 s quite sim-

shot	P_{aux}	Density	Flux	Inlet	a1	a2	a3	retained	
	kW	10^{19} m^{-3}	10^{20} at/s	at	10^{20}	10^{20}	10^{20}	10^{20}	%
25052	900	5.0	10	52.7	9.8	10.3	18.8	13.9	26
25053	900	2.1	5	27.3	3.0	8.2	15.7	0.3	1
25064	900	1.8	5	28.2	1.6	5.0	12.1	9.5	34
25065	900	4.2	10	52.8	4.9	10.9	19.2	17.7	33
22974	8000	10.3	250	947.0				$\approx$ 10	1

FIG. 4: *Global plasma parameters, results of exponential fits and calculated retention of discharges operated without pumping.*

ilar to that of the expansion time of neutral gas in the vessel as measured by fast gas inlet without magnetic field. This time constant was fixed when fitting the longer term decay. To get a reliable fit two more decay times are needed, as shown by the straight line in Fig. 3. The second time constant is obtained with 14.2 s the third one with 199 s. The time constant of about 200 s seems to be typical for outgassing of room temperature components in AUG. For example the quartz mirco balance monitors installed below the divertor to monitor the growth of deposited layers [10] show a decrease of the layer thickness after a discharge with a time constant of 200 - 300 s. After 300 s the pumping valves are opened and the vessel is pumped down for the next discharge. To get the complete inventory the exponential functions are integrated. To enable a comparison of the different discharges, the time constants obtained are fixed for the following fits of the amplitude from the three components (Table: 4).

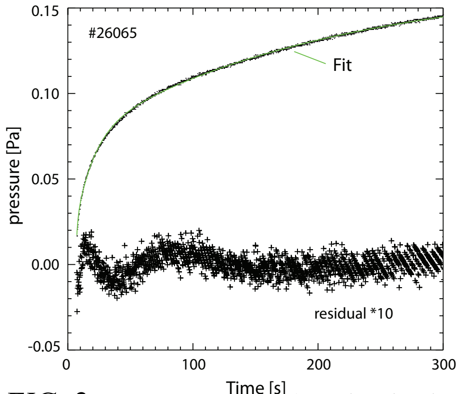

FIG. 3: *Pressure rise after the discharge together with the fit using three exponentials. To show the quality of the fit the residual (*10) is also indicated.*

As stated above the first investigations were performed during an operational day after some other discharges. The cryo pump was warmed up to liquid nitrogen temperature and the wall was depleted using 5 Min HeGD before the experiments. The first useful discharge was # 25052, a 5 sec long ECRH auxiliary heated H-mode discharge with a high gas flux. The retention yielded by the fitting procedure described amounts to $13.9 * 10^{20}$ or 26 % of the gas input. This result is in line with the C-mod observations. In the following discharge the gas input was reduced by a factor of 2 and almost no retention was observed. Obviously the long term retention depends in AUG strongly on the history of the preceding discharges. To minimize these effects the discharges were repeated as the first ones of an operational week. During the weekend the cryopump was warmed up and in the morning the wall inventory was minimize by 15 min of HeGD. This time, the investigations started with the low density discharge followed by the one with higher gas input. The absolute retention was $9.5 * 10^{20}$ at D for the low density and $17.7 * 10^{20}$ at D for the high density discharge. Normalized to the gas input, the retention in both discharges is 33%. Both results are again in the range of the typical retention described at Alcator C-Mod which are in the range $6 - 30 * 10^{20}$ depending on the plasma density. Obviously, the earlier apparent discrepancy of the C-mod and AUG results seems to be due to the different amount of gas puffed during the discharges. Comparing # 25052 and # 25065 the strong variation of the retention by 25 % reflects the influence of the wall history in AUG. The absolute retention for typical H-mode discharges (# 22974), performed with high gas puff and neutral beam heating, yields a quite similar value in the range of $10 * 10^{20}$, even though the accuracy of these measurements is lower. The data and the magnitudes of the three exponentials are summarized in Table 4 together with an earlier result for an H-mode discharge using the dynamic gas balance method. The inventory of the first component is always about twice the plasma inventory at the end of the discharges. This points to the fact that, as shown in Fig. 2, the plasma inventory and the neutral gas at the divertor are comparable. In Fig. 5 the amplitudes of the exponentials for the discharge pair # 25064/05 are shown. The component presenting the neutral gas is less than 10 %, whereas the faster outgassing component contains about 20 % of the inlet. 40 % of the puffed gas is found in the component with the longest time constant. Gas which is released on longer time scales, as known from the pressure measurements during weekends are counted as retained in these investigations. As the component with the slowest outgassing contains most of the gas inlet, small errors in the fitting procedure restrict the accuracy of these investigations to about 1-2 %. For this reason it was not possible to measure the retention in AUG as accurate as in C-mod. For metal walls deuterium is retained by adhesion at the surface or diffusion inside the surface layers [11,12]. In principle both processes could be distinguished by the time constants of the outgassing. At AUG only W coatings with a typical thickness of some microns are used. The typical W diffusion time constant at 500 K is a few *μm* during 5 s, the typical discharge time. Due to this short time is seems almost impossible to distinguish both processes in real AUG discharges. Surface contamination due to typical plasma impurities additional complicates the situation. A more plausible explanation of the two time constants are the different surface temperatures in the vessel after the discharge. Again not the average temperature of a tile has to be taken into account, but only the surface temperature. Even for the low heated discharges reported above the surface will be heated to 500 K at the plasma wetted areas as the divertor and the protection limiters, i.e. a faster outgassing is expected for these areas. However most of the surfaces are located at remote areas and will remain at room temperature, i.e. the outgassing is expected on a longer time scale. Of cause the plasma wetted areas are much less than the 20 % as expected from the data. Moreover one has to take into account not only the geometrical surface but also the fluxes to this areas, as long as no saturation occurs. At AUG the inner divertor is the region of highest plasma and neutral fluxes, but due to the shallow magnetic field angle, it was not possible to derive reliable values from the Langmuir probe data up to now.

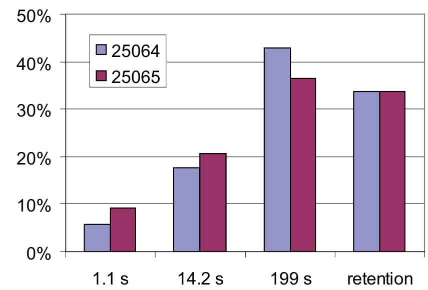

FIG. 5: *Comparison of the normalized fractions of the components with different decay time for the discharges 25064 and 25065.*

3. Gas balance measurement for typical discharges

Previous investigations were done after the damage of one fly-wheel generator used for AUG, which reduced the maximum shot duration. After the recommissioning of this generator, typical discharges are repeated with a longer flat top phase. To investigate the pure tungsten surface, all PFCs are cleaned during the vent from boron layers by water wiping. In total 3 series of discharges were performed for gas balance investigations. Reliable gas balance investigations require a well conditioned device. So the experiments were done after 1100 discharge just before and after the first boronisation of the campaign. To get the pumping speeds as accurate as possible, the cryo pump was warmed up after each discharge and releases its inventory into closed the vessel. Unfortunately these data are not evaluated up to now, but will be part of a future publication. The first series compromised typical 1*MA* H-mode discharges at intermediate auxiliary heating with different gas puffing rates.

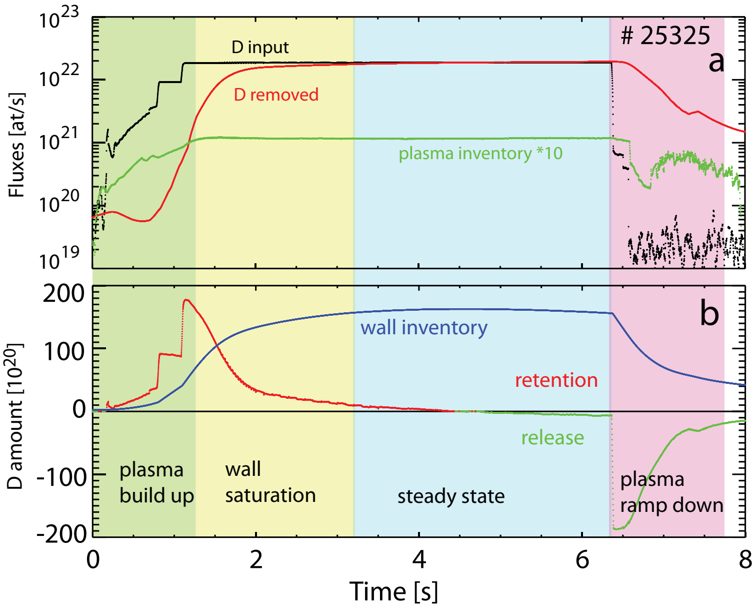

FIG. 6: *Phases of the wall retention. At a the D input and removal is shown. The steady state phase is indicated in bluecyan. The fluxes to the PFCs and the wall inventory is shown in b.*

During the second series discharges with large auxiliary heating were performed. The most interesting discharges were repeated as third series after the boronisation. Data evaluation was done using the same procedure as discussed in a previous paper [5], only the pumping speeds of the turbo pumps was recalibrated, as the type of pumps was changed in-between. The amount of gas puffed, which is the most relevant parameter for wall saturation, was enhanced by 50 % and previous results could be confirmed with a higher accuracy: After loading up the wall a steady state phase was reached, during which the retained amount of gas is in the percent range, i.e. zero within the error-bars of the measurements [5].

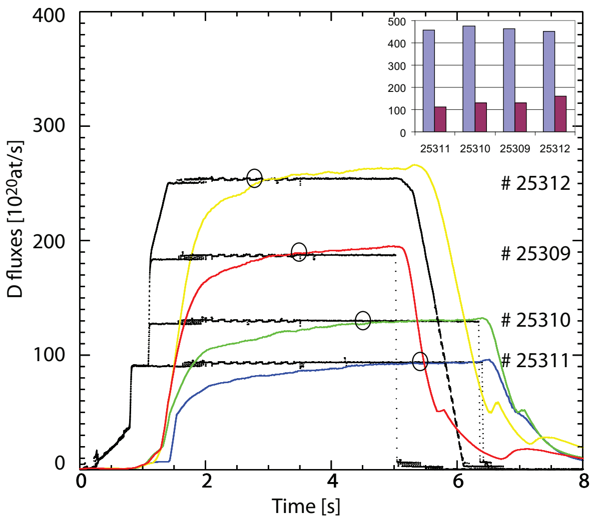

FIG. 7: *D inlet and pumped D for 4 similar discharges with different gas fluxes. The time where the pumping rate equals the injection rate is indicated by a circle.*

The D input, pumped gas and plasma inventory of a typical discharge, operating without the turbopumps, are shown in Fig. 6 a. This H-mode discharge uses 5 MW of NBI and 0.8 MW of ECRH to avoid W accumulation. A gas puff of $2 * 10^{22}$ at D was used to reach a plasma density of $9.5 * 10^{19}$ m^{-3}. The Fig. 6 shows only the time of the discharge without the period of outgassing after the current ramp down. As described above the typical phases are observed: plasma density build up (till 1.2s) wall saturation (till 3.15 s) steady state (till 6.2s) and divertor ramp down (till 7.8s). Again the time constant to get a stable pumping is much longer than the time needed to build up the plasma density. After this, a 3.3 s long steady state phase is reached, during which $370 * 10^{20}$ at D are puffed and $376 * 10^{20}$ at D are pumped. This leads to a small negative retention (gas release) of $6 * 10^{20}$ or 2 % of the amount of gas puffed. The release is rising during this phase, presumably due to warming up of the walls. On the other hand an accuracy of a few percent is expected from the calibrations. As soon as the gas puff is shut down, strong outgassing occurs. The outgassing changes on a time scale of 1.0 s, i.e. the typical time for neutral gas redistribution and the fastest time scale which could be measured by the experimental set up. This finding hints to the fact that the gas is stored only dynamical at the wall: during a gas puff as much gas is injected to the PFCs as released by the PFCs. In Fig. 6 b this is illustrated by the injection and release rate shown in red and green. In the first phase the wall storage dominates, than a long phase with almost no net D storage follows. The switch off of the gas puff leads to a strong outgassing, during the plasma ramp-down. The integral (in blue) shows a maximal wall inventory during the discharge of $157*10^{20}$ at D, which is reduced to $41*10^{20}$ at D or 4 % of the amount of gas puffed already till the end of the plasma current. After this the typical outgassing, as discussed above starts. Another aspect is the question, how to reach the steady state conditions. Former investigations indicated that the amount of gas retained, not the gas puffed is the key parameter for wall saturation. This behavior is expected from the surface activation: if enough D is bond to the surface, no active voids are available anymore and a new D atom can be only stored, if another D atom is released from the surface or the near surface layers. To verify this picture, 4 identical discharges are performed and only the gas puff rate was varied. The results are summarized in Fig. 7 and Table 8. The pumped D is continuously rising and equals the gas input after some time. This time varies with the gas puffing rate: for high gas puff saturation is reached already after 2.8 s, whereas for the lowermost one 5.6 s are needed. For guiding the eyes this timepoint is indicated by a circle. The amount of gas puffed until this moment and the retained gas are indicated in the insert as blue and red bars, respectively. Almost no variation of the input gas and the retention is found. Obviously the wall saturation depends mostly on the total amount of gas puffed. For the higher puffing rates some outgassing probably due to wall heating is observed at the end of the steady state phase.

shot	puff rate	time	gas inlet	gas retention
	10^{20} at/s	s	10^{20} at	10^{20} at
25311	100	5.6	458	113
25310	140	4.5	475	129
25309	200	3.4	464	131
25312	270	2.8	451	160

FIG. 8: Data of the discharges shown in Fig. 7. The 3 right rows refer to the time point indicated.

4. Influence of Boronisations

Another question is the role of boronisations on the wall retention. Boron layers are used in most fusion devices as oxygen getter to reduce the impurity content. For pure tungsten investigation the boron layers in AUG had been completely removed for two subsequent campaigns. No boronisations were performed during this time. After this procedure no significant boron signal was observed by spectrocopy anymore. For the total cleaned AUG a typical wall inventory of $200*10^{20}$ at D was needed to reach the steady state phase. During the 2008/09 campaigns boronisation was used again and the amount of gas needed for wall saturation was reduced to $1.5*10^{22}$ at D [6]. During the 2009 campaign AUG was operated again with pure tungsten PFCs, i.e. boron layers had been completely removed during the vent. After the initial conditioning phase an wall inventory of only $1.2-1.5*10^{22}$ at D was needed for saturation. This

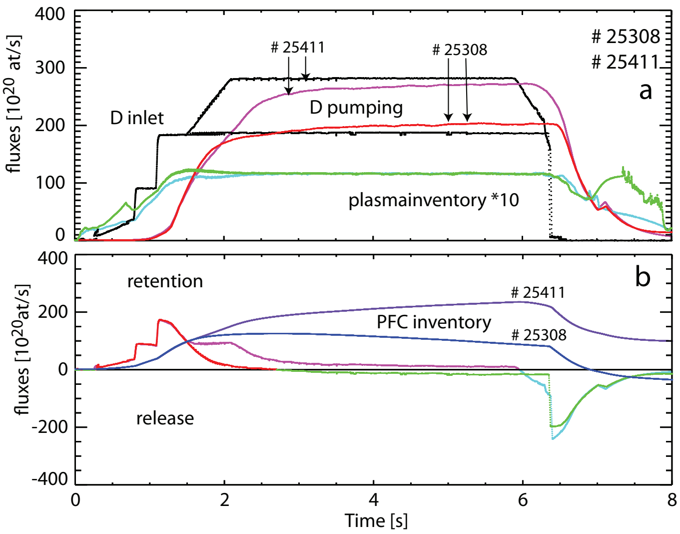

FIG. 9: Nominally identical discharges without and with boronisation. In a) the D input, pumping (# 25308 in red, # 25411 in magenta) and plasma inventory are shown. In b) the retention is indicated in blue for the non boronised and in purple for the boronized discharge.

value did not change significantly after boronisations. Only one wall cleaning seems to be not sufficient to remove the boron layers completely. Boron layers on PFCs with high fluxes are eroded within 100 discharges, whereas the layers at more remote areas are almost unchanged till the next vent. At AUG boronisations are used to enable low density high edge temperature discharges and therefore no high density shots, which will load the wall are performed with a fresh boronisation. To fill this gap a typical H-mode discharge was done just before and as soon as possible after the first boronisation at the 2009 campaign. To get identical global parameters additional gas had to be puffed for the density build up: obviously the wall acts as additional pump (Fig. 9). From the view of neutral gas the start up phase till 1.5 s is identical, even after the saturation is reached (after 3.5 s) the behavior is quite similar. The only, but crucial difference is that for # 25308 the discharge removes gas from the PFCs during this phase, whereas the discharge after boronisation (# 25411) shows a continuous retention. To saturate the wall the unboronized discharges needs an inlet of $404 * 10^{20}$ at D leading to a wall retention of $123 * 10^{20}$ at D after 3 s. Till the same time point the boronized shot needs $527 * 10^{20}$ at D and a wall load of $193 * 10^{20}$ at D was build up. The boronized PFC pump a much bigger amount of D. This is illustrated in Fig. 9 b, where the inventory of the wall is shown. The clean wall has a lower inventory, which is reduced during the discharge, whereas the boronized wall acts as a getter and accumulates additional D. New boron layers may influence significantly gas balance measurements.

5. Summary

Previous investigations, which showed a steady state phase after saturation of the wall could be confirmed with higher gas input. The saturation depends on the total amount of gas retained. Operation without pumping allows to identify 3 different time constants for the outgassing after a discharge. The first component can be identified to be the neutral gas and plasma inventory, second one the outgassing from hot surfaces and finally the one with the longest decay time of 200 s the outgassing from cold surfaces, which contains about 40 % of the gas puffed. The absolute amount of retained gas observed is in close agreement with typical H-mode discharges. A fresh boronisation needs more gas to be retained to reach wall saturation. After some time, when the boron is removed from high flux components, the retention is again reduced.

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