

Wall retention of deuterium and gaseous impurities in all tungsten ASDEX Upgrade

V.Rohde, A.Kallenbach, V.Mertens, R.Neu and ASDEX Upgrade Team

Max Planck Institut für Plasmaphysik, EURATOM Association, Garching, Germany

E-mail: Rohde@ipp.mpg.de

Abstract. The tritium inventory is one critical issue of the present ITER design. Gas balance measurements in all tungsten ASDEX Upgrade show different phases of a semi-detached H-mode discharge. After the limiter start-up, the wall is loaded during a high retention phase. After this a steady state retention is reached. During this phase only $1.5 \pm 3.2\%$ of the puffed D atoms are retained in the vessel. During plasma ramp down outgassing of the wall starts, resulting in a remaining inventory of about 1.6 % 10 s after the discharge. The low retention is confirmed by post mortem analysis of tiles. To reach steady state a wall loading of typical $1.9 \cdot 10^{22}$ D atoms is needed. After applying boronisation only $1.4 \cdot 10^{22}$ D atoms are sufficient. The mechanism of this transient wall loading is still unclear, but from the amount of gas needed it seems to be plausible that not only the divertor, but all in-vessel components are involved.

Residual gas analysis is hampered by uncertainties of the $H/(H + D)$ ratio for the different water and hydrocarbon molecules. Especially water seems to be produced by outgassing of in-vessel components. Nevertheless a first evaluation yields a D content of hydrocarbons of about 1 %, which has only a minor effect for the gas balances.

1. Introduction

Today most of the fusion devices are using plasma facing components (PFCs) consisting of carbon. Whereas graphite is beneficial for present experiments, the high erosion rate and especially the co-deposition of hydrogen isotopes with the eroded carbon will be a critical issue in a future fusion reactor. In ITER the amount of tritium stored in the vacuum chamber has to be kept below the total amount of T allowed by the site licensing. Alternative PFCs are high Z materials, which will have a much lower H retention, but are more critical in view of the plasma performance. To test this, all plasma facing components in ASDEX Upgrade (AUG) were exchanged from carbon to tungsten during the last years [1]. The reduction of the carbon deposition was demonstrated using marker tiles and post mortem analysis of the PFCs by ion beam techniques [2,3]. These measurements provide only campaign averaged information, whereas time resolved data are needed to identify scenarios, which cause high retention. To extrapolate from present day short discharge lengths to ITER pulses, the temporal evolution of the retained gas during a discharge is needed. Only gas balance measurements yield time resolved information on the retained D.

The basic idea of gas balances is to measure the retained gas from the difference of the gas input to the amount of removed gas. Comprehensive investigations had been done in the super conducting tokamak Tore Supra, which provides shot lengths up to 400 s [4,5]. Retention of 50 % of the amount of gas puffed was found, but the puffing rate was, as usual for limiter devices, as low as only $3 \cdot 10^{20}$ at/s. To reduce the power load to the divertor plates, ITER has to operate in semi-detached divertor conditions. To reach this operation regime high gas flows are needed in the scrape off layer. For example a gas puff of $3 \cdot 10^{22}$ at/s is needed to reach a semi-detached divertor for the standard H-mode discharge in AUG. To measure gas balances under these conditions highly accurate calibrations of the gas inlet and pumping systems are needed. Extensive gas balance work has been also done at JET [6].

2. Experiments

Deuterium is injected into AUG by the gas inlet valves and the neutral beam heating system. The gas is pumped by the torus pumping system, the in vessel cryo pump and the neutral beam injection (NBI) boxes. All these systems are calibrated with respect to one high accuracy capacitive pressure gauge. The measured pumping speeds are nearly proportional to the pressure, demonstrating the restriction of the pumping speeds by the conductance in the vessel. Details of the calibrations are discussed in [7,8].

Recently high accuracy gas balances had been reported for Alcator C-mod [9]. These experiments are done without active pumping, which allows to measure the non retained gas by the pressure in the vessel 10 minutes after the discharge. The same idea was used at AUG to calibrate the pumping speed of the in vessel cryo pump. These static measurements yield high accuracy results, but in AUG the experiments would be

restricted to non relevant discharges, i.e. mainly discharges with ohmic heating.

As AUG is operated with tungsten wall and without wall coatings, like boronisation, the impurity behavior is quite critical. Regular ELM's, which flush the impurities out of the pedestal, are needed for stable high performance discharges [10]. Additionally a collision dominated flow towards the divertor plates is desired. Consequently the gas balance deals with the difference of big quantities, which is limited by the accuracy of the individual calibrations. Another problem is the gas temperature, which needs to be known to derive particle fluxes from the pressure measurements. The liquid N_2 shielding of the cryopump, which influences about 10 % of the vessel volume, is always kept at 70 K. On the other side, radiation shielding of some diagnostics are designed with low thermal contact, to reduce the power flux to the instruments and to keep the surfaces clean. After a high power H-mode discharge these parts reach temperatures up to 400 K after 10 min. So the gas temperature in AUG is not homogenous. To estimate the effective gas temperature a known small amount of gas was injected into the closed vessel after plasma discharges. From the pressure rise the effective gas temperature could be deduced. For different discharges it varies between 285 K and 300 K, leading to an error of 1.5 % for the amount of gas.

The gas balance measurements under consideration were performed during the 2008 campaign under non-boronised conditions [11]. Commonly wall coatings as amorphous boron layers are used as wall conditioning technique in fusion devices. The main purpose of these boron layers is to getter O, which affects the plasma performance. In high-Z devices these low-Z layers are additionally used to cover the surface, i.e. to reduce the impurity production. To investigate the pure tungsten surface, all layers had been removed during a vent and AUG was operated without wall coating during the 2007 and parts of the 2008 campaign. The data discussed in this paper have been collected after the initial conditioning (# 22764) till the first boronisation (# 23093)[7]. Almost no boron had been observed by spectroscopy during this time [11].

As database for the gas balance the standard H-mode discharges in AUG is used. This is a typical semi-detached 1 MA discharge with 5 MW neutral beam heating and a line averaged density of $9 \cdot 10^{19} m^{-3}$. This discharge scenario is used as basis for many different experiments. The flat-top length of this discharge is about 5 s, much less than the discharge time in ITER. Therefore a careful analysis of the time dependence of the retention is needed to extrapolate for long duration discharges.

3. Phases of a discharge

In view of gas balances a typical AUG discharge consists of 5 different phases: limiter, wall loading, steady state, ramp down and finally outgassing phase (see Fig. 1). The plasma is started in a limiter configuration, which requires only low D puff of typical $7 \cdot 10^{20}$ at/s. Although the pumping speed is quite low in a limiter configuration, the gas balance depends strongly on the wall conditioning. For the gas balance of the whole discharge this phase is negligible. After typical 0.4 s the divertor is formed and

the plasma density and current are ramped up to the flat-top value. Plasma flat-top conditions are reached at 1 s, but the time to establish steady state conditions for the gas inventory is 2.4 s. If the puffing rate is not high enough, the steady state phase may not be reached until the end of the discharge. Here we refer to the data of the standard H-mode discharge [12] # 22820, which uses an average puffing rate of $1.9 \cdot 10^{22}$ at/s during the wall loading phase. The retention during the wall loading phase varies, but on average 40 % of the puffed gas is retained. In total $5.0 \cdot 10^{22}$ D atoms had to be puffed to reach the steady state phase, which leads to a dynamic retention of $2.0 \cdot 10^{22}$ D atoms. As AUG operates with a semi-detached divertor the high gas puffing rate of $3.6 \cdot 10^{22}$ at/s is continued. The divertor pressure adjusted itself so that, within the error-bars of the measurement, the same amount of gas ($3.6 \cdot 10^{22}$ at/s) is pumped. To estimate the retention of long term discharges, this phase has to be extrapolated. Unfortunately, it was not possible up to now to extend the flat top time to 10 s, as it will be possible with the restored fly wheel generator. The discharge is smoothly ramped down to avoid disruptions. During this phase the gas puffing is strongly reduced to $6.7 \cdot 10^{20}$ at/s. Now the wall starts to outgas and $5.3 \cdot 10^{21}$ at/s are removed. In total $1.2 \cdot 10^{22}$ D atoms are pumped during the plasma ramp down, i.e. $8.9 \cdot 10^{21}$ D atoms remain in the vessel at the end of the discharge. This equals to 9 % of the amount of gas puffed. The discharge ends with a minor disruption, which has no significant influence on the gas balance. After the discharge the outgassing phases starts. During the first 10 s after the discharge additional $7.4 \cdot 10^{21}$ D atoms are pumped. Only an inventory of 1.6 % of the gas puffed remained after this time in the vessel. Measurements of the long term outgassing for this discharge is disturbed by the progressing operation.

More accurate data could be gathered using all similar discharges during the interval mentioned above. In total 24 discharges are available, which show some variation on the gas input due to variations of the shot programm. If the integral over the whole discharge is used for the gas balance $1.1 \cdot 10^{21}$ at/s or $8.2 \pm 3.3\%$ of the puffed gas is retained during the shot. If one compares the relative values, the retention in AUG during a discharge is by a factor of 2 to 5 less than at other devices [4]. From the time evolution it is clear that one has only to extend the steady state phase to extrapolate for long time discharges. During the steady state phase a retention of only $1.5 \pm 3.2\%$ is found. The error, taken from the statistical variation, indicates that the accuracy reached is not sufficient to distinguish whether deuterium, additionally to the wall loading, is retained during this phase or not.

In relation to the total amount of gas puffed, the amount of retained gas is quite low. On the other hand, if one takes the average value of $2.7 \cdot 10^{20}$ at/s this is almost the same absolute amount as in Tore Supra. One has to keep in mind that the neutral particle fluxes to the wall in AUG are more than 2 orders of magnitude larger than in a limiter device.

The amount of deuterium retained was also measured post mortem by ion beam analysis of tile and collection probes. For tungsten PFCs the total amount of deuterium found equals to 0.5 % of the gas input [3]. These kind of investigations yields always a

lower limit of the total retention, as some deposition areas may be not covered by the analysis. After the outgassing, a retention of about 1 % is derived from the gas balances. In contrast to ion beam investigations gas balances yield an upper limit, as some gas will outgas on a long time scale. Variations of the base pressure due to warming up of the cryo pump and other events did not allow to measure this fraction with an sufficient accuracy. Even for the low retention found, the gas balance and the probe analysis show very good agreement within the error-bars.

4. Wall saturation

The amount of gas retained during a discharges in AUG is restricted by the wall saturation. The occurrence of saturation affects the extrapolation to long term discharges significantly. Wall saturation is reached if the amount of puffed and pumped gas during a are equal at any given time . For tungsten PFCs this is always observed, if a high enough amount of gas is puffed. The amount of gas which has to be puffed to reach saturation for the data set mentioned above is shown in Fig. 2. On average a gas input of $5.4 \cdot 10^{22}$ D atoms is needed to load the wall. The variation of this amount by a factor up to 1.6 indicates that other parameters, as for example the variation of the pumping efficiency by the strike point position, affects this value. The amount of gas retained is also plotted in Fig. 2. These data show much less variation, indicating that the amount of retained gas does not strongly depend on the plasma properties. On average the wall has to be loaded with $1.99 \pm 0.14 \cdot 10^{22}$ D atoms to reach saturation.

No D is retained in AUG if D molecules are injected without plasma operation. The retention must be due to D ions, atomic D or an activated surface. As the surface activation is by ions or atomic D, the amount of retained gas should be normalized to the flux of these species towards the PFCs. Unfortunately, these fluxes in AUG are presently not known with the required accuracy. A more refined data analysis may be available in the future. Here we restrict ourselves to a more qualitative interpretation. The ion flux is concentrated to the divertor plates, which has a wetted area of about $0.5m^2$. If only ions are involved at the divertor, a deposition of about 4000 mono-layers [ML] is required, too much for a surface adhesion. If this amount is dissolved in the tungsten layers with an atomic fraction of 0.1 the top 4 microns of the layers will be filled. In the divertor PVD and plasma sprayed tungsten coatings are used in AUG. The gas retention of these layers depends on the individual production mechanism, no literature values are available. On the other hand atomic D is also produced by ions and radiation at the main chamber. If we assume a uniform distribution of the retained gas at the main chamber, only a 40 ML deposition is expected (for the geometrical surface). This value is still too high for a pure surface layer, but neutral species can reach also side surfaces and structural material. Additionally, the true surface roughness has to be taken into account: the real surface area will be larger. Another hint for the storage process is the behavior after boronisation. To saturate the wall, higher puffing rates have to be used. During the 2008 campaign boronisations are used to investigate low

density scenarios. For this reason no high gas puff shots had been done with a fresh coating. The long term behavior of this campaign reveals however that the amount of gas needed to reach steady state conditions drops continuously (Fig. 3). At the end of the campaign only $1.4 \cdot 10^{22}$ D atoms are retained in the wall when saturation is reached. This can be explained, if the effective surface area of the layers were reduced by erosion or more plausible as influence of the boron coatings. More investigations on the storage process are obviously needed.

The plasma discharge was ramped down smoothly to avoid disruptions. Soon as the gas puffing rate is reduced the outgassing of the wall starts and the in-vessel inventory is reduced. The typical time constant is equal to the capacity of the pumping system. The retained wall inventory seems to be a dynamic equilibrium of D capture and release at the vessel. The influence of the boronisation, which does not coat the divertor, and the total amount of gas hint that the D is stored not only at the divertor, but at the whole vessel.

5. Residual Gas Analysis

Analysis of the residual gases offers additional insight into the gas storage mechanism. AUG is equipped with several residual gas analyzers (RGA) based on the quadruple principle. These instruments are commonly used for gas analysis, but in a tokamak environment some restrictions have to be overcome. The first problem is the magnetic field: ions are used inside the quadruple mass filter. Even small magnetic fields can influence the calibration of the instruments significantly. Consequently the instruments are shielded and mounted far away from the divertor. To deal with the typical divertor pressure during discharges differential pumping is needed. The mounting position results in an effective possible time resolution of about 300 ms. To deal with the different requirements three instruments are mounted at AUG. A standard type is located at a main chamber port, it operates without magnetic shielding and differential pumping system. This allows a high sensitivity, but the instrument can be used only in between discharges. The second one is a commercial one designed for high pressure operation. This type uses a very short quadruple, which restricts the mass resolution. But the short analyzer tolerates a higher residual magnetic field, so the size of the shielding could be minimized. This instrument is mounted at the same position as the divertor capacitive gauge. The third instrument is a high resolution type, which allows to separate the He peak from the D peak. This instrument is mounted at a remote position, the operation during discharges is quite critical. During a plasma discharge the instruments are switched into the peak jump mode, i.e. only some discrete masses are measured to enable a sufficiently good temporal resolution. The instruments are calibrated using a test gas mixture with the same kinds of hydrocarbons as observed after a plasma discharge.

As a first step a whole spectrum obtained shortly after a discharge was fitted to a model for the residual gas. The model contains the following molecules:

He, Ne, Ar, H₂, D₂, N₂, O₂, CO, CO₂, H₂O, CH₄, C₂H₄, C₂H₆ and different combinations, where H is substituted by D. Unfortunately some peaks of the spectrum are produced by more than one species. A fitting procedure takes this into account, but the accuracy reached for some molecules is limited. A real problem arises due to the hydrocarbons. AUG is routinely operating in D, but some H remained due to the non perfect baking of the carbon tiles. After the initial conditioning typically $H/(H + D) < 0.05$ is found in the main plasma. As the residual gas is more influenced by the wall, a higher hydrogen content is expected there. To deal with this problem we measure $H/(H + D)$ by the high resolution RGA and use this value for the data evaluation. Theoretically calculated cracking patterns for the molecules mentioned above are available [13]. Using the $H/(H+D)$ ratio obtained from the hydrogen molecules, no satisfactory fit of the model to the data was possible. It turned out that the $H/(H + D)$ ratio for water and hydrocarbon are different from the hydrogen molecule value. A $H/(H + D) = 0.1$ is found for hydrogen molecules, $H/(H + D) = 0.15$ for the hydrocarbons but $H/(H + D) = 0.8$ for water. The high ratio for water suggests that most of the water is produced by outgassing of the wall after the discharge. Even though the PFCs are tungsten coated, the tiles contain about 1 ton of graphite, which can be baked only to 150°C in AUG. So the release of hydrogen dominated water after a discharge is plausible. Clearly, a more refined model seems to be necessary to get a realistic $H/(H + D)$ ratio in the residual gas during discharges.

As an example the spectra after the discharge # 23968, which uses a N₂ puff for divertor cooling are evaluated. In Fig. 4 the results of the fit, which takes the different $H/(H + D)$ ratio into account are shown. Here, 97.5 % of the residual gas is D and He. The high He content is due to a calibration pulse just before the data are taken and the fact, that He is only pumped by the turbo pumps, so that it is enriched for the pumping system. The dominant impurity is water, which is produced by outgassing of hot PFCs. A significant amount of N₂ (3500ppm) but no oxygen ($\leq 10ppm$) is observed. For discharges without nitrogen seeding, no significant amount of N is found. CO and CO₂ sum up to 400ppm, reflecting the low oxygen content of the discharges after a boronisation, hydrocarbons are dominated by methane (6200ppm), higher hydrocarbon molecules are about 100ppm.

The effect of the hydrogen containing residual gas can be neglected for the gas balances. A high He content could cause a problem for gas balances. The He is implanted in the PFCs by HeGD before a discharge and is released during the shot. This would lead to an overfilled gas balance, as the pumping speed of the cryopump is overestimated. For this reason HeGD was omitted for the discharges used for the gas balances above.

6. Summary

Gas balance measurements in AUG with all tungsten PFCs are presented. A typical semi-detached H-mode discharge consists of different phases. First, the wall is loaded

with $1.99 \pm 0.14 \cdot 10^{22}$ atoms D. After this, a steady state phase, during which only $1.5 \pm 3.2\%$ of the puffed D is retained, is reached. Most of the wall inventory is pumped during plasma ramp down and during the first 10 s after the discharge. The remaining D inventory derived from gas balances is compatible to the amount measured by post mortem analysis. The gas loaded at the wall is only dynamically retained, as it will be released during ramp-down and shortly after the discharge. The total amount stored and the influence of the boronisation suggests that the whole first wall and not only the divertor stores the D. The amount of gas needed to saturate the wall is reduced after boronisations. Residual gas analysis are hampered by the different $H/(H + D)$ ratio for hydrogen, methane and water molecules. The total amount of hydrocarbons is less than 1 % and dominated by methane. To enhance the accuracy of the measurements the torus pumping system of AUG will be fitted with a special volume, which stores the pumped gas and enables high accuracy measurements. The evaluation of the residual gas will be used to study surface processes involved.

7. Acknowledgements

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8. References

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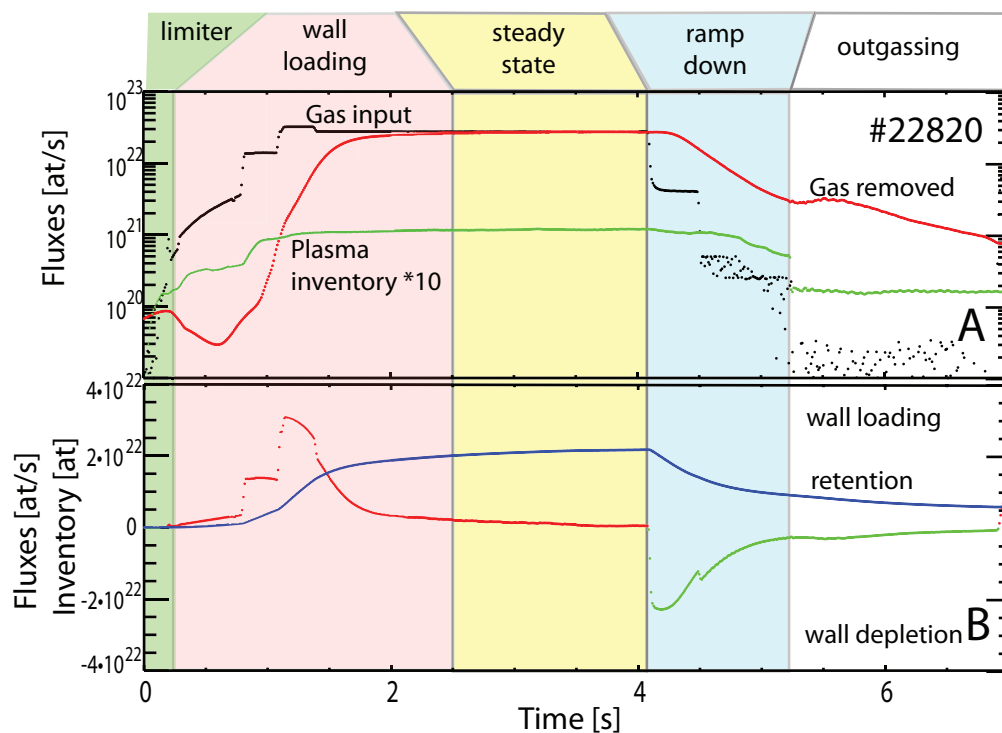


Fig.1 : Gas balance of the discharge # 22820 showing the different phases of the retention. In Fig. 1A the gas input is plotted in black and the gas removed in red. For comparison the content of the plasma discharge, scaled by a factor of 10 is also shown. In Fig. 1B difference of the gas input and gas removed is displayed. Wall loading is indicated in red, wall depletion in green. The temporal integral of this value, indicating the wall inventory, is additionally shown in blue.

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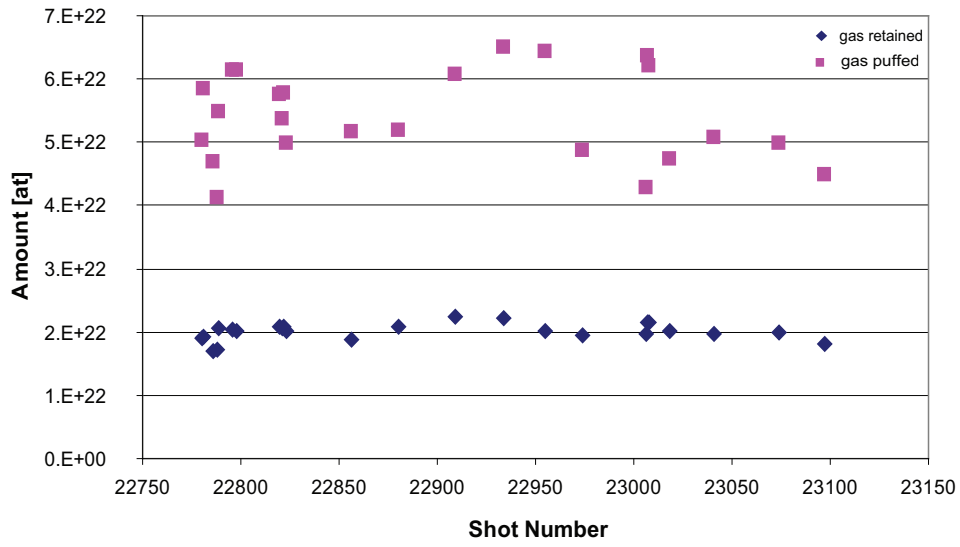


Fig.2 : The amount of gas puffed needed to reach the steady state phase for the data set mentioned in the text is shown in magenta. The transient wall retention to is shown in blue.

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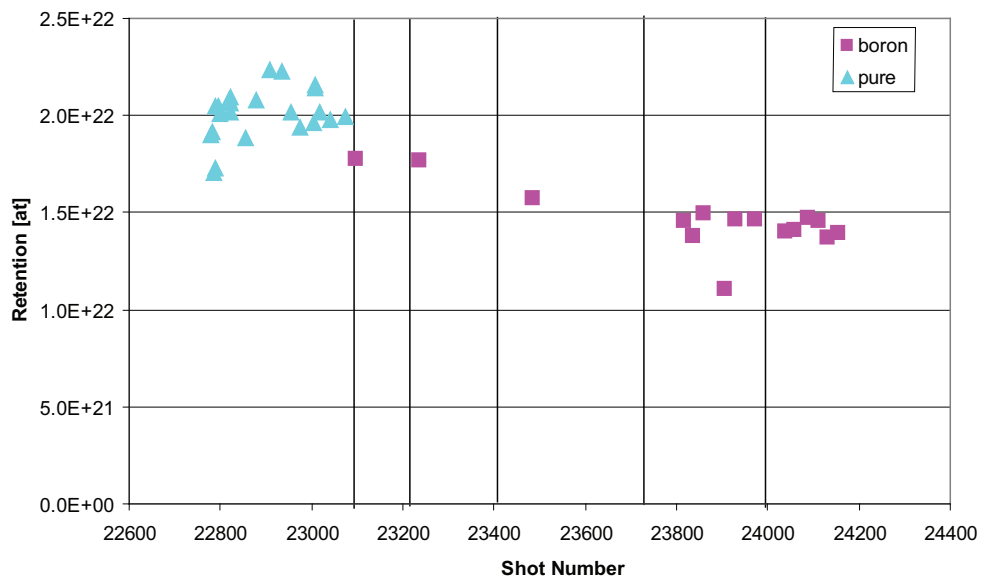


Fig.3 : Wall retention needed to reach steady state conditions. The cyan triangles show the data for non boronised wall (same data set as used in Fig 2). The retention after boronisations (indicated by vertical lines) are shown as magenta squares.

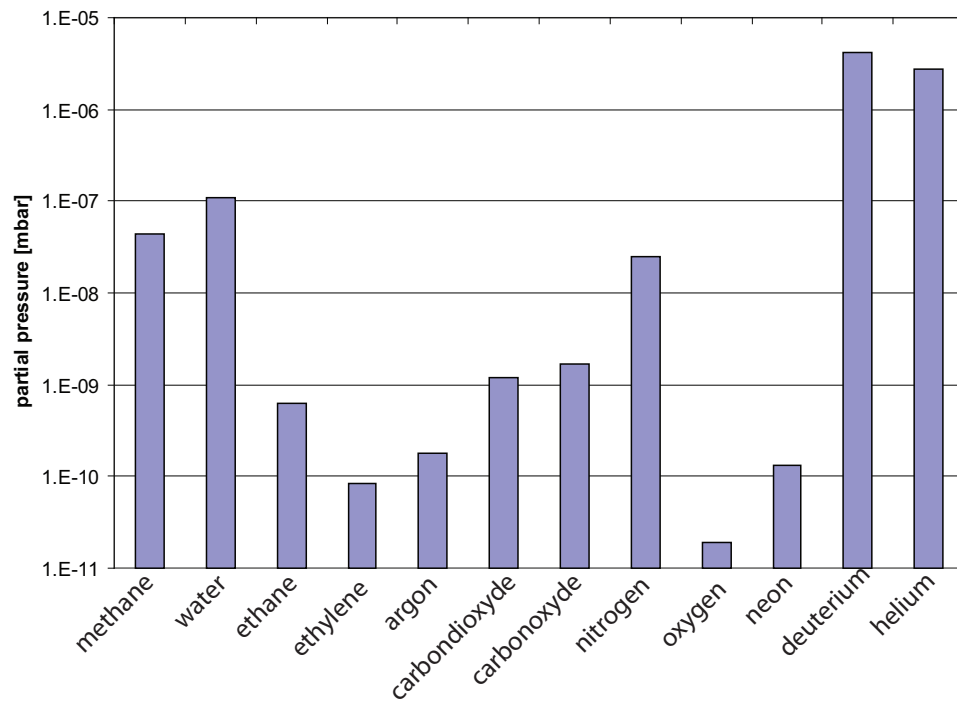


Fig.4 : Result of the residual gas analysis after the shot # 23968. The molecules used for the fit are shown at the abscissa. Different $H/(H + D)$ ratios are considered for molecule hydrogen, water and hydrocarbons.