ELSEVIER

Journal of Nuclear Materials 266–269 (1999) 1065–1071

journal of nuclear materials

Dynamic hydrogen retention in the walls of the tokamaks ASDEX Upgrade and DIII-D

G. Haas [a,*], R. Maingi [b], J. Neuhauser [a], ASDEX Upgrade team [a], DIII-D team [c]

[a] *Max-Planck-Inst. für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, D-85748 Garching, Germany*
[b] *Oak Ridge National Laboratory, Oak Ridge,TN 37831, USA*
[c] *General Atomics, San Diego, CA 92121, USA*

Abstract

The large dynamic particle inventory on the wall is investigated in ASDEX Upgrade and DIII-D with a fast local particle balance. Certain events (e.g. disruptions or ELMs) lead to an inhomogeneous neutral pressure distribution in the vessel, e.g. between main chamber and divertor region. We measure the pressure equilibration of this inhomogeneous distribution and estimate wall outgassing or pumping rates necessary to satisfy the particle balance. Detailed particle balances for the divertor of ASDEX Upgrade after disruptions reveal large additional source and sink terms which decay with time constants of 10–20 ms over up to three orders of magnitude. Taking into account the finite pump time constants of the divertor chambers, ad- and desorption times of the order of 1 ms can be derived. Corresponding studies on DIII-D confirm these results, but with a larger spread of the decay times (10–80 ms). The divertor pressure evolution after ELMs in both tokamaks also confirms the existence of such a fast reservoir.

Keywords: Wall particle content; Particle recycling; Desorption; Activation energy for desorption

1. Introduction

It is generally observed on divertor tokamaks that only 10–20% of the gas puffed in during plasma build up appears finally as plasma or neutral gas in the torus [1,2]. Most of the ''missing'' particles are not permanently buried or lost, but are transiently adsorbed on the wall and are involved on a short time scale in the recycling process.

The wall inventory, i.e. the amount of gas actually stored on the wall, can be evaluated simply by a global particle balance, but the distribution in the torus, the wall materials mainly involved and the adsorption mechanism are widely unknown. One can learn more about the wall reservoir, i.e. the ability of the walls to transiently store particles, by studying the pressure relaxation after fast events which leave behind a strongly inhomogeneous pressure distribution like disruptions or ELMs. Ad- or desorption on the wall causes sink or source terms in a fast local particle balance during the pressure relaxation.

After a disruption leads to the inhomogeneous pressure distribution in the vessel the plasma has disappeared and a quantitative particle balance is possible considering only volumes, conductances and pumping speeds. The wall condition may be modified by the disruption itself, e.g. part of the wall inventory may be deposited during the disruption. Issues which can be addressed are the size of the reservoir, the balance between adsorbed gas and neutral pressure in the volume, adsorption mechanism or adsorption times and energies.

After an ELM the wall condition is typical for the discharge. But the presence of plasma allows only a qualitative analysis, e.g. an estimation of relaxation times. ASDEX Upgrade (Fig. 1) and DIII-D (Fig. 2) are well qualified for such investigations. Both are equipped

* Corresponding author. Tel.: +49 89 3299 1459; fax: +49 89 3299 2580; e-mail: ggh@ipp-garching.mpg.de

0022-3115/99/$ – see front matter
PII: S0022-3115(98)00561-3

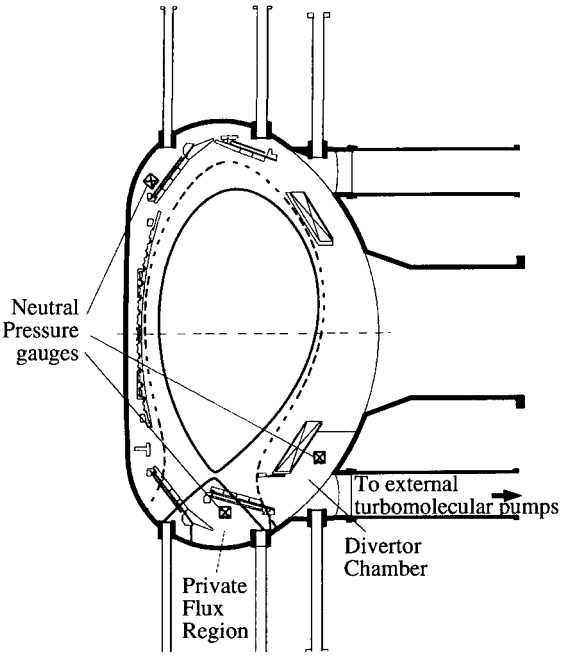

Fig. 1. Cross section of ASDEX Upgrade with the position of the neutral pressure gauges and other features relevant for this study.

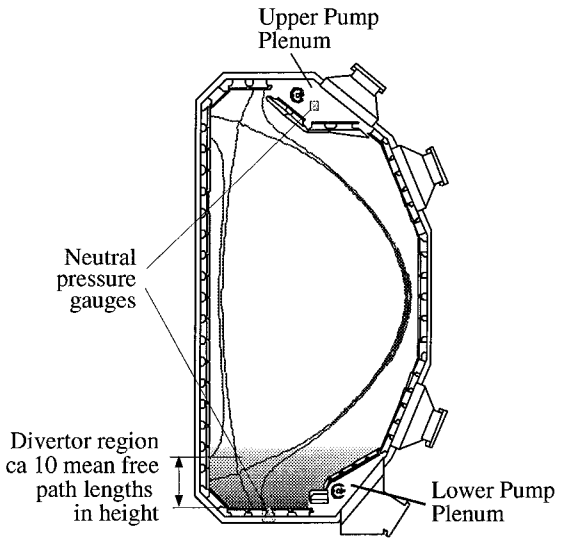

Fig. 2. Cross section of DIII-D with the position of the neutral pressure gauges and other features relevant for this study.

with fast in-vessel pressure gauges (response time 1–2 ms) [1,3,4]. There are no large chambers with slow connection to the main chamber which would mask the wall effect by their own time constant.

2. Particle balances after disruptions

In ASDEX Upgrade and DIII-D single null down divertor discharges are considered. No internal cryo pump has been used. As in other elongated tokamaks disruptions are usually accompanied by a vertical instability (Vertical Displacement Event). Mostly the plasma is dumped into the divertor (VDE down) producing a much larger pressure rise and wall load in the divertor than in the remaining vessel. However, occasionally the plasma is dumped in the opposite direction (VDE up) with the pressure rise in the divertor slower and smaller than in the remaining vessel. Additionally when the gas load of the divertor during the preceding discharge is small, the pressure in the main chamber may become higher than the divertor pressure. In both cases the analysis of the pressure relaxation between divertor and main vessel allows to study transient adsorption processes on the walls in the divertor with time scales in the ms range.

2.1. Model and geometry

The objects of this study are conditions and processes in the divertor, not in the main chamber. Particle balances are done for volumes and walls in the divertor, only. Pressures have to be measured in both parts of the vessel, the main chamber pressure, however, serves as a reference, only.

2.1.1. ASDEX Upgrade

In the previous ASDEX Upgrade divertor (Div I) two well-defined chambers existed (Fig. 1), the private flux region (PFR) below the X-point and the divertor chamber behind the passive stabilization loop (Div). Their volumes V_{PFR} and V_{Div}, the conductances C_{PFR} and C_{Div} to the main chamber, the pumping time constants τ_{PFR} and τ_{Div} and the pumping speed of the external turbo molecular pumps C_{TP} connected to the divertor chamber are given in Table 1. The conductances and the pumping speed are given for molecular flow condition. The increase in the transition flow range is taken into account for the analysis. The values in Table 1 are expected to be accurate within 25%

The particle balance of the PFR can be expressed by

$$\frac{\mathrm{d}p_{\mathrm{PFR}}}{\mathrm{d}t} V_{\mathrm{PFR}} + (p_{\mathrm{PFR}} - p_{\mathrm{Ves}}) C_{\mathrm{PFR}} = S_{\mathrm{PFR}} \qquad (1a)$$

with p_{PFR} and p_{Ves} being the pressures in the PFR and the vessel, respectively and S_{PFR} an additional source term caused, e.g. by ad- or desorption processes.

One gets the balance equation for the divertor chamber by replacing the PFR related quantities (subscript "PFR") with the corresponding quantities related to the divertor chamber (subscript 'Div') and adding a

Table 1
Parameters of the ASDEX Upgrade divertor

	Private flux region	Divertor chamber
Subscript	PFR	Div
Volume V	1.25 m^3	1.72 m^3
Conductance to main vessel C	220 m^3/s	390 m^3/s
Pumping time constant $\tau = V/C$	5.7 ms	4.4 ms
External pumping speed C_{TP}	none	13 m^3/s

term to the left hand side representing the pumping by the external turbo molecular pumps

$$\frac{dp_{Div}}{dt} V_{Div} + (p_{Div} - p_{Ves}) C_{Div} + p_{Div} C_{TP} = S_{Div}. \quad (2)$$

Using the measured pressures and the quantities given in Table 1 Eqs. (1a) and (2) can be integrated numerically. In all cases investigated we have found a non-zero source term, positive after a VDE down and negative or positive after a VDE up. For a negative term the gas load of the divertor during the preceding pulse has to be very low. Otherwise the vessel pressure will not exceed the divertor pressure. The typical positive source term can be described as superposition of a large but fast exponentially decaying contribution and a minor slowly decaying or even constant one. The second may decay exponentially, too, but then with a time constant exceeding the observation time. We consider the slow contribution as the beginning of the well-known long term outgassing which has been measured on other tokamaks up to hours after a discharge and is usually described as $\propto t^{-(0.7\pm0.2)}$ [5]. After subtracting such a background one gets a clear exponential decay with a time constant of about 10–20 ms sometimes over nearly three orders of magnitude. (see Fig. 3 below) The very few examples of a negative source term show no slow component. In this paper we will deal with the fast component. For the quality of its exponential fit the assumed time dependence of the slow one is only marginally important, but for mathematical simplicity an exponential fit is convenient. In the following only the equations for the PFR are explicitly discussed.

The source term can be identified with ad- or desorption on the chamber walls

$$S_{PFR} = -A_{wPFR} \frac{dn_{wPFR}}{dt} / N_A. \quad (3)$$

There is n_{wPFR} the density *per unit area* of particles adsorbed on the walls, and $N_A = 2.5 \cdot 10^{22}$ D_2/m^3 mbar. A_{wPFR} the surface area of the walls in the PFR.

As we will show later the fast decay of the source term indicates a thermal desorption rate of the order of 1000 s^{-1} which corresponds for room temperature to a binding energy of a few 10^{-1} eV/particle. That excludes implantation, chemisorption or adsorption involving dissociation, which are higher energy processes. Additionally we observed similar decay rates for positive and negative source terms. In the latter case after the disruption gas is streaming into the divertor and the process is definitively dominated by adsorption of molecules in the divertor and not by desorption of particles which may be deposited on the wall during the disruption itself. After the disruption the available energies per molecule are insufficient for implantation or dissociation.

Therefore we assume a first order adsorption process of molecules which can be described by

$$\frac{dn_{wPFR}}{dt} = \varphi_{PFR}(v_{PFR} - n_{wPFR})\sigma_{ad} - \frac{n_{wPFR}}{\tau_w} \quad (4a)$$

v_{PFR} being the density *per unit area* of traps, σ_{ad} the adsorption cross section, $1/\tau_w$ the thermal desorption rate and $\varphi_{PFR} = p_{PFR} N_A \bar{v}/4$ the neutral flux density of the gas (with $\bar{v}$ mean velocity of the molecules).

With $\langle \varphi_{PFR} \rangle = \frac{1}{t} \int_0^t \varphi_{PFR}(t')\, dt'$ the neutral flux density averaged for the time period $0 < t' < t$ Eq. (4a) can be solved analytically:

$$\frac{n_{wPFR}(t)\, A_{wPFR}}{A_{wPFR}\, v_{PFR}\, \sigma_{ad}} = \exp(-(\sigma_{ad}\, \langle \varphi_{PFR} \rangle + 1/\tau_w)t) \left[\int_0^t \varphi_{PFR}(t') \exp((\sigma_{ad} \langle \varphi_{PFR} \rangle + 1/\tau_w)t')\, dt' + \frac{n_{wPFR}(0) A_{wPFR}}{A_{wPFR} v_{PFR} \sigma_{ad}} \right]. \quad (5)$$

About 20 ms after the disruption the integration is started ($t = 0$). The wall inventory at this time, $n_{wPFR}(0)A_{wPFR}$, can be derived by integrating the exponential fit for the fast component of the source term from 0 to ∞.

To get an impression of the qualitative behavior of the volume and wall inventories we consider a case with $n_{wPFR} \ll v_{wPFR}$ and $p_{Ves} \ll p_{PFR}$. This may be not fulfilled shortly after the disruption when the gas load of the wall may reach saturation level and late in the decay when p_{Ves} approaches p_{PFR}. But between it is a good approximation.

We introduce $n_{PFR} = N_A p_{PFR}$ the particle density *per unit volume* in the private flux region and three characteristic rates, $1/\tau_{PFR} = C_{PFR}/V_{PFR}$ the pumping rate of

the PFR, $1/\tau_{ad} = A_{wPFR} v_{PFR} \sigma_{ad} \bar{v}/4/V_{PFR}$ the rate with which molecules become adsorbed in the PFR, $1/\tau^*$ the measured decay rate of the fast component of the source term.

Eqs. (1a) and (4a) become linear with these assumptions:

$$\frac{dn_{PFR}}{dt} + \frac{n_{PFR}}{\tau_{PFR}} = -\frac{A_{wPFR}}{V_{PFR}} \frac{dn_{wPFR}}{dt}, \tag{1b}$$

$$\frac{dn_{wPFR}}{dt} = n_{PFR} \frac{\bar{v}}{4} v_{PFR} \sigma_{ad} - \frac{n_{wPFR}}{\tau_w}. \tag{4b}$$

An analysis of these simplified differential equations shows that during a start phase n_{PFR} decays faster than n_{wPFR}. During the following stationary phase both quantities drop exponentially with the same rate which can be identified with $1/\tau^*$. Eqs. (1b) and (4b) yield

$$1/\tau_w = 1/\tau^* + \frac{\tau_{PFR}}{(\tau^* - \tau_{PFR})\tau_{ad}} \tag{6}$$

We have several unknown coefficients (the parameters of the slow component, $\sigma_{ad}, A_{wPFR} v_{PFR} \sigma_{ad}$), which are expected to be constant at least during the decay after one pulse. They have to be determined step by step by comparison with the experimental results. The steps for deriving the coefficients are:

1. Determination of the total source term by numerical integration of Eqs. (1a) or (2).
2. Subtraction of an appropriate slow background from the source term so that the remaining fast component decays exponentially down to signal noise.
3. Calculation of the thermal desorption rate $1/\tau_w$ from Eq. (6) with an estimated τ_{ad}.
4. Variation of σ_{ad} in Eq. (5) so that the variation in time of the 'adsorbing area' on the walls $A_{ad} = A_{wPFR} v_{PFR} \sigma_{ad}$ becomes a minimum during the decay.
5. Calculation of an improved τ_{ad} with the new A_{ad} and iteration of the last three steps 3, 4 and 5.

2.1.2. DIII-D

This model can be applied also to DIII-D slightly modified for the different geometry (Fig. 2). DIII-D has no well-defined divertor chambers. The pump plenum which may be considered is too small and its vacuum time constant too long to contribute to a fast source term. The pressure drops continuously from the bottom of the vessel towards the top. The divertor pressure is measured by a gauge installed in a recess in the lower divertor plates looking upwards. It averages over a few mean free path lengths in the neutral gas. We consider as "divertor region" this volume above the lower target plate, e.g. 10 mean free path lengths in height. This choice may appear arbitrary. It has, however, no influence on the proof of the existence of an additional source term from the wall. The conductance from the divertor region to the top of the vessel is so large, that the vacuum time constant is below 1 ms. This is less than 10% of the shortest decay time observed (see Section 2.2.2). This question has to be discussed, however, in more detail, if one tries to derive also from the DIII-D data ad- and desorption times. For the conductance the whole vessel is considered as an annular slit. Transition flow effects are taken into account. The reference pressure in the main chamber is measured by a gauge installed in the upper pump plenum. The readings of it were corrected for a time constant of 30 ms.

2.2. Results

2.2.1. ASDEX Upgrade

Fig. 3 shows results of a fast particle balance for the divertor chamber. Data for other discharges are summarized in Table 2. The procedure described at the end of Section 2.1.1 works fine for most of the unknown coefficients except for σ_{ad}. It is remarkable that the thermal desorption rate is much faster than the decay of the source term. The "adsorbing area" is within a factor of three constant from shot to shot, but the adsorption cross section changes over a large range which is implausible. One finds values between 10^{-23} and 10^{-19} m^2. The reason is that as long as most traps are empty, i.e. the wall is far from saturation (expressed in Table 2 by the degree of coverage θ), only the product A_{ad} of the

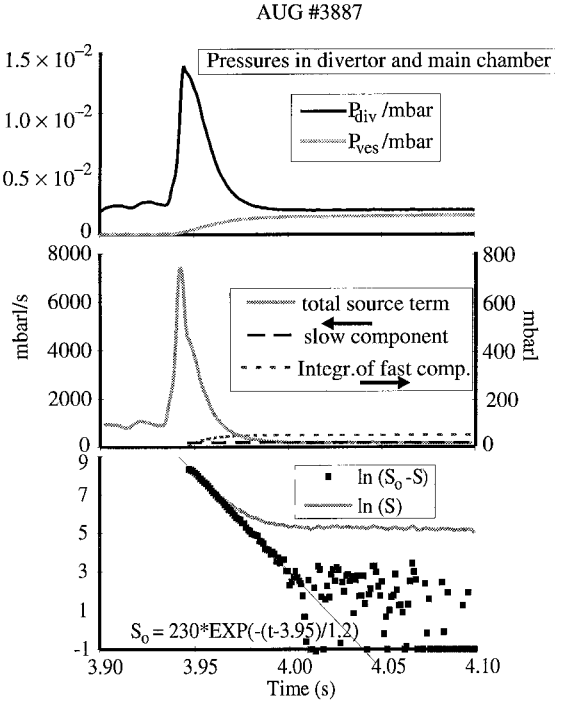

Fig. 3. Fast particle balance for the divertor chamber of ASDEX Upgrade after a disruption. The straight line in the lower part corresponds to a decay time of about 10 ms.

Table 2
Results from ASDEX Upgrade

#	Slow component		Fast component					
	τ	amplitude	τ^*	A_{ad}	σ_{ad}	τ_w	τ_{ad}	θ
			Private flux region					
3887	1.2	6.25×10^{21}	9.08	9.91	1.0×10^{-20}	0.24	0.41	7.90
7958	0.5	5.0×10^{20}	18	9.23	3.8×10^{-20}	0.9	0.44	17.8
8042	0.9	1.50×10^{21}	7.60	3.34	1.0×10^{-22}	0.38	1.21	0.21
8043	0.7	1.75×10^{21}	11.50	3.89	1.0×10^{-23}	0.97	1.04	0.03
			Divertor chamber					
3887	1.2	5.75×10^{21}	9.65	17.20	2.0×10^{-20}	0.37	0.32	17.00
7958	–	0	17.5	18.9	1.0×10^{-19}	0.83	0.29	30.9
8042	0.9	1.50×10^{21}	15.10	21.20	2.5×10^{-21}	0.61	0.26	1.50
8043	0.7	1.75×10^{21}	16.50	33.80	6.0×10^{-20}	0.44	0.16	37.80
	s	D_2/s	ms	m^2	m^2	ms	ms	%

number of traps and their cross section can be determined. The number of traps $A_{wPFR} v_{PFR} = A_{ad}/\sigma_{ad}$ and the cross section σ_{ad}, can be separated only if the wall is partially saturated. Mostly saturation is reached only during and immediately after the disruption. At this time a detailed analysis is difficult.

2.2.2. DIII-D

Fast particle balances during the decay after disruptions at DIII-D show a similar additional source term. There is a large exponentially decaying component on top of a small nearly constant background. Fig. 4 shows an example with a decay time of 11.5 ms. The decay times show a broader distribution (see Table 3), but the shortest times are the same as in ASDEX Upgrade excluding an effect of vacuum time constants. The longer times observed in some of the DIII-D cases (they are over represented in Table 3) may be caused by the fact that in DIII-D the walls in the divertor have direct contact with the plasma during the discharge whereas in ASDEX Upgrade they have not. We found some correlation between the longer decay times and the discharge duration, the total gas puff and the divertor pressure before the disruption as shown in Table 3. Particle balances with slower decay may be dominated by particles which are slightly stronger bound. There is, however, also the possibility that the unexpected long decay times are caused by the assumed pressure and time dependence of the divertor volume. This needs a more detailed discussion which is beyond the scope of this paper.

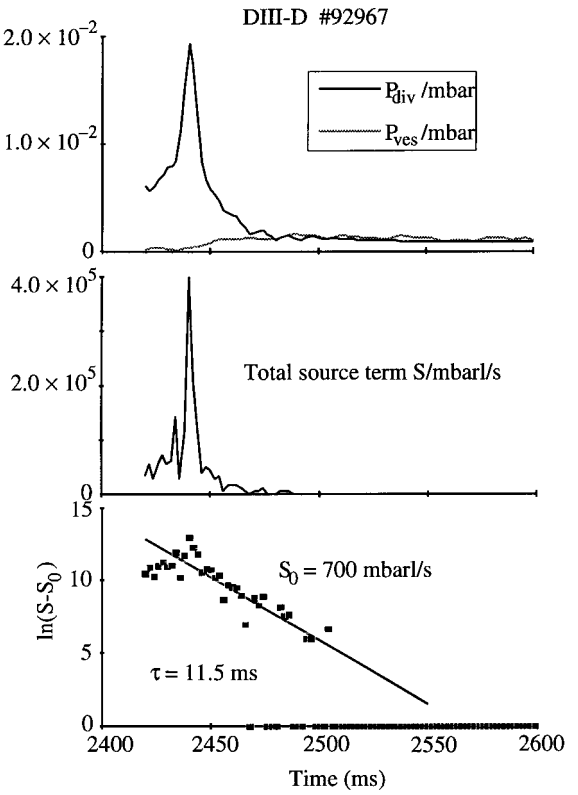

Fig. 4. Fast particle balance for the divertor region of DIII-D after a disruption. The straight line in the lower part corresponds to a decay time of about 10 ms.

3. Pressure development after ELM's

After an ELM the neutral gas pressure in the divertor especially in the private flux region rises. The increase does not start before the ELM characterized by the H_α signal is nearly completed. The pressure maximum is reached typically 10 ms later in both tokamaks as shown in Fig. 5. This behavior confirms qualitatively the results from the particle balances after disruptions. A quantitative particle balance is impossible. Especially during and after an ELM the role of the plasma as source and

Table 3
Parameters of DIII-D pulses

#	92967	92968	92971	
Decay time	11.5	33	80	ms
Pulse duration	2430	3190	3310	ms
Divertor pressure before disruption	2.7×10^{-3}	1.1×10^{-2}	1.3×10^{-2}	mbar
Total gas puff during discharge	150	300	285	mbar l

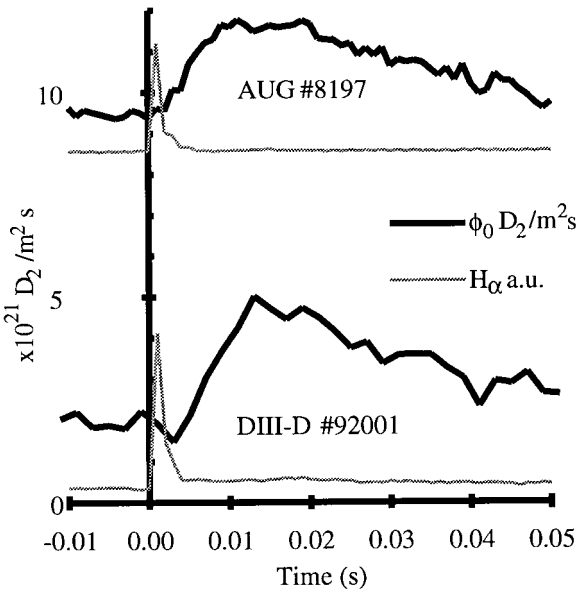

Fig. 5. Comparison of the divertor neutral flux density during arbitrarily chosen ELMs in ASDEX Upgrade (PFR) and DIII-D. The H_α traces are shown as time markers. The main difference is the higher pressure in the divertor of ASDEX Upgrade which is responsible for higher H_α signal and neutral flux density between ELMs in ASDEX Upgrade. The origin of the time base has been shifted in both cases to the onset of the ELM.

sink of neutrals can not be calculated with sufficient accuracy.

4. Adsorption model

High thermal desorption rates of the order of 1000 s^{-1} on walls at room temperature are compatible with binding energies of several 10^{-1} eV excluding chemisorption or implantation. Such values are only slightly above the range reported in the literature for physical adsorption by van der Waals forces in the undisturbed systems hydrogen/graphite and hydrogen/metal [6–10]. It seems reasonable to attribute the found reservoir to physical adsorption activated by the plasma. The fact that we see qualitatively the same behavior after an ELM excludes the disruption as only origin of the traps. A rather good particle accountability of prefill and gas puffs 1 or 2 s after the discharge indicates a short life time of these traps themselves.

5. Conclusion

Fast particle balances after disruptions for the divertor regions in ASDEX Upgrade and DIII-D show an additional exponentially decaying source term which is caused by sorption processes on the wall. Especially the analysis of data from ASDEX Upgrade indicates ad- and desorption times around 1 ms. Integrating the fast source term delivers up to three times as many particles as are present in the volume at the time of the pressure maximum. The fast exchange in combination with the size explains the important role which this wall inventory plays for the whole discharge. It disappears within 100 ms after the discharge. It is completely decoupled from the known long term inventory which is built up by implantation or codeposition and usually investigated by analysis of probes after the discharge.

This study has to be considered as a start. We plan to extend it with an improved model and by investigating more discharges. The pulse by pulse variation of quantities like τ_w, A_{ad} or τ_{ad} which are expected to be constant is too large to be caused by data scatter only. It may also indicate that some of the assumptions made are too simple. It is, e.g. questionable that all traps have identical τ_w instead of a distribution.

Acknowledgements

This work was supported in part by US DoE under Contract No. DE-AC05-960R22464 with Oak Ridge National Laboratory and DE-AC03-89ER51114 with General Atomics.

References

[1] G. Haas, J. Gernhardt, M. Keilhacker, E.B. Meservey, The ASDEX Team, J. Nucl. Mater. 121 (1984) 151.
[2] G. Haas, H.S. Bosch, A. Kallenbach, C. Klepper, R. Maingi, D. Meisel, W. Poschenrieder, ASDEX Upgrade

team, NBI team Proc. of 22nd EPS Conf. on Contr. Fusion and Plasma Phys., vol. 1, Bournemouth, 1995, p. 321.
[3] C.C. Klepper, T.E. Evans, G. Haas, G.L. Jackson, R. Maingi, J. Vac. Sci. Technol. A 11 (1993) 446.
[4] G. Haas, H.-S. Bosch, 2nd Otto von Guericke Workshop on Problems of Vacuum Measurement, 3–5 June 1997, Magdeburg, Germany; vacuum 51 (1998) 39.
[5] V. Philipps, J. Ehrenberg, J. Vac. Sci. Technol. A 11 (1993) 437.
[6] R.M. Barrer, Proc. Roy. Soc. A 161 (1937) 476.
[7] W.G. Frankenburg, J. Am. Chem. Soc. 66 (1944) 1827.
[8] S. Brunauer, The adsorption of gases and vapors, Physical Adsorption, vol. 1, Princeton University Press, Princeton, NJ, 1945.
[9] S. Dushman, J.M. Lafferty, Scientific foundation of vacuum technique, Sorption of Gases and Vapors by Solids, 6, Wiley, New York, 1966.
[10] J.P. Hobson, Physical adsorption, in: V. Jayadevaiah R. Van selow (Eds.), Surface Science: Recent Progress and Perspectives, Crit. Rev. Solid State Sci. 4 (1974) 221.