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A B S T R A C T

Recycling has been studied in the DITE tokamak by changing the working gas from hydrogen to deuterium and back to hydrogen. The change in the composition of the plasma has been followed both during the discharge and from shot to shot using a scanning Fabry Perot interferometer, a mass spectrometer and a carbon thermal desorption probe. The results of the three techniques are consistent and show that the gas trapped and desorbed from the wall plays a major part in the recycling process. A detailed analytical model of the principal recycling mechanisms is proposed.

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1. INTRODUCTION

The fact that tokamak discharges can be sustained for many particle confinement times is a clear indication that wall recycling is an important process. In many tokamaks[1,2] the density is observed to increase with time indicating a net flux of particles from the wall into the discharge. In tokamaks where the walls have a low gas concentration of adsorbed and trapped gas, for example when using titanium gettering,[3] it has been shown that recycling at the wall is reduced and the electron density decreases with time. However, even when the density is constant or decreasing with time it has been shown that there is rapid exchange between the plasma and the gas on the torus wall.[4] Using a mass spectrometric technique it was observed that the amount of gas which evolved from the walls was greater than that expected due to surface adsorption and it was concluded that this concentration is built up by ion trapping in the surface over a number of discharges.[5]

It is known that in principle, there are a number of different physical processes involved in recycling, such as ion backscattering, particle induced desorption and thermal gas release.[6] The present experiments were carried out in an attempt to elucidate the detailed mechanisms responsible. In order to be able to distinguish between the gas pulsed into the torus at the start of the discharge and that already trapped in the walls during previous discharges we have studied the transition from discharges in one gas, hydrogen, to another, deuterium.

2. EXPERIMENT

The DITE tokamak has been described in detail in earlier publications.[7,8] The present experiments have been carried out at plasma currents of 50 kA and 100 kA without the divertor or neutral injection. The gas filling is by means of a piezo electric valve which is normally opened 100 ms before the start of the discharge. The valve is open for 70 ms and admits typically 0.3 Torr-ℓ of the working gas. The mean electron density is monitored during the discharge using a multi-channel 2 mm microwave interferometer. No detailed measurements of the density or temperature profiles have been made but the discharges are similar to those previously described.[8] Three techniques are used for monitoring the behaviour of hydrogen and deuterium:

The probe is mounted on a bellows drive unit which can be remotely driven in or withdrawn from the torus. It is normally exposed to a single discharge and then withdrawn into a separate valved-off vacuum chamber where it is heated, by passing a current through it, to a temperature of 1300 K to desorb the trapped particles. The gas released is analysed with a Q7 mass spectrometer used in the scanning mode. The carbon probe therefore samples the total particle flux arriving at the wall integrated over a single discharge. It has a lower detection limit of 10^{13} atoms cm^{-2} determined by neutral gas adsorption on its surface.

3. RESULTS

The behaviour of the hydrogen and deuterium during the discharge is observed with the Fabry Perot interferometer and results are shown in Figure 1 for 50 kA discharges in deuterium following many discharges in hydrogen. The first two discharges in deuterium at 100 kA are shown in Figure 2. The mass spectrometer showed that the filling gas was > 98% deuterium. Figure 3 shows the ionization spike which illustrates that initially the discharge was more than 75% deuterium. It is observed that the ionization peak of deuterium appears $\sim$ 0.3 ms earlier than that of hydrogen. This behaviour is reversed when changing from deuterium back to hydrogen discharges. At later times the H_α line increases in relation to the D_α line and we observe that the ratio $D_\alpha/(H_\alpha + D_\alpha)$ changes from greater than 0.5 at 20 ms to become almost constant 0.35 at later times. Since the central ion containment time has been measured to be 40 ms, we consider that at later times in the discharge an equilibrium has been reached and that the fluxes of hydrogen and deuterium entering the discharge are representative of the relative gas concentrations on the wall and in the plasma. In successive discharges the equilibrium proportion of deuterium slowly rises and the equilibrium value at 100 ms is plotted as a function of discharge number in Figure 4. It can be seen that over a number of discharges the deuterium concentration increases asymptomatically to a value of $\sim$ 80%. In Figure 4 we have also plotted the relative values of the hydrogen and deuterium trapped in the carbon probe which represent an integral of the flux of atoms and ions leaving the plasma during the pulse. It is seen that these results agree very well with the equilibrium values obtained from the Fabry Perot interferometer.

the plasma phase to be N_p and that trapped in the wall to be N_w. Where there is only one species we will have:

$$\frac{dN_w}{dt} = \frac{N_p}{\tau} - \beta \frac{N_p}{\tau} - \alpha N_w \frac{N_p}{\tau} \tag{1}$$

where τ is an average containment time for ions and atoms, β the average reflection coefficient, and α is a coefficient of the form $\alpha = \sigma/A$, where A is the area of the wall taking part in the interaction and σ is the detrapping cross section. The first term in equation (1) is the particle flux to the wall, the second is the backscattered flux and the third the flux released by particle bombardment. The backscattered and particle induced fluxes will correspond to the high and low energy components respectively in the neutral flux into the plasma.[10] During the time-scale of the discharge the total number of particles in the torus must be conserved, $N_p + N_w = N$, and thus if the density in the discharge remains constant so must the density in the wall.

$$\frac{dN_w}{dt} = 0 = (1-\beta) - \alpha N_w$$

$$\text{i.e. } n_w = N_w/A = (1-\beta)/\sigma \tag{1a}$$

A typical value[6] for the equilibrium concentration on the wall is $n_w = 5 \times 10^{15}$ cm^{-2} and this indicates a value for the particle induced release cross section $\sigma \simeq 1 \times 10^{-16}$ cm^2.

Now consider the situation where there are two gases, hydrogen and deuterium, of wall populations N_{wH}, and N_{wD}, and plasma populations N_{pH} and N_{pD} respectively

$$N_{wH} + N_{wD} = N_w \text{ and } N_{pH} + N_{pD} = N_p = Vn_p \tag{2}$$

where V is the volume of the plasma and n_p the mean density.

We also have conservation of the total number of atoms of each species so that:

$$N_{wH} + N_{pH} = N_H \text{ and } N_{wD} + N_{pD} = N_D \tag{3}$$

We can write down an expression similar to equation (1) for the rate of change of the hydrogen component of the wall population:

Now for the first discharge the filling gas is composed entirely of one species (D_2) and the wall is loaded only with the second species (H_2), i.e. at t = 0, we have $N_{wD} = 0$ and $N_{wH} = N_H = An_w$ and from (7)

$$T \equiv \frac{F_D}{F_H+F_D} = \frac{\beta N_D}{\alpha N_H N_p+\beta N_D} = \frac{\beta}{\sigma n_w+\beta}$$

which is again the expected result. We have already shown (equation 1a) that $\sigma n_w = 1-\beta$, if the density remains constant, and thus at the start of the first discharge $T = \beta$.

Assuming that the energy of the plasma ions arriving at the wall is 30 eV we obtain $\beta \simeq 0.6$ from the universal curve of particle reflection coefficient vs Lindhard reduced energy ε.[6] From the experimental results in Figure 2 the ratio of deuterium flux to total flux at early times corresponds to a reflection coefficient β of 0.55, which is in good agreement with the above estimate. The total amount of gas in the wall phase is obtained from the equilibrium value of N_D/N_H at the end of the discharge. The only other parameters required to calculate F_D/F_H are the value of plasma density which is obtained experimentally from the microwave measurements (assuming $n_p = \bar{n}_e$) and the particle containment τ_p. It is not necessary to know σ explicitly. The particle containment time which must be used is a global average including both ions and neutrals. From a model of the charge exchange and ionisation processes[10] we find that neutral particle recycling dominates. Since we have measured, from Hα emission profiles, an average ion containment time of $\sim$ 30 ms we estimate that τ is of the order of a few ms. The theoretical equilibrium time τ^1 is approximately 1.5 τ for the range of conditions used. Experimentally we observe that equilibrium is established over a much longer time scale, Figure 2, and we interpret this to be due to a secondary effect - a partial loss of deuterium in the wall during a discharge. Such an effect is observed in ion beam experiments and is due to atoms being trapped at damage sites with high binding energies and not being released.[11] These sites must be filled before simple ion induced detrapping of the form assumed in the recycling model is observed. Some loss may also be due to diffusion of deuterium away from the surface into the bulk.

From the equilibrium at the end of the discharge we obtain the ratio of deuterium to hydrogen effectively in the system. Since we know the amount of deuterium introduced we can readily deduce the amount of hydrogen

results from the Fabry Perot and carbon probe in Figure 4. The close agreement indicates that the rate of loss of gas between discharges is proportional to the amount of gas present in the discharge.

However if there was a fixed amount of hydrogen available in the wall then we would expect the hydrogen concentration to decay exponentially to zero over a series of discharges. On the contrary all the results show that the hydrogen decays more slowly than exponentially indicating an additional source of hydrogen into the system. This is clear from Figure 4, since the proportion of deuterium does not increase to 100%.

We have interpreted this source as being partly due to hydrogen slowly diffusing from the bulk of the wall material to the surface layer and partly to deuterium diffusing into the solid. In any single discharge we would expect that only the atoms which are within the range of the incident energetic plasma ions, i.e. perhaps within $\sim$ 10 nm of the surface, are released. However, if the walls have been subjected to ion bombardment over a long period of time, there will have been diffusion into the bulk, resulting in an equilibrium hydrogen concentration to some depth into the metal. When the hydrogen in the surface layer is depleted by ion induced release during a discharge we would expect the hydrogen in the bulk to diffuse back to the surface. From extrapolation of data at higher temperatures[12] we estimate that the diffusion coefficient of hydrogen in austenitic stainless steel at 300 K is $\sim 10^{-13}$ to 10^{-12} cm^2 s^{-1}. The time between shots is typically 6 minutes and hence the characteristic diffusion length is 100 nm - quite sufficient to replenish the surface layer from the bulk. Further evidence that this is the real explanation of the hydrogen behaviour is obtained from Figure 5 where the hydrogen and deuterium outgassing rates are observed as a function of time after a discharge. It is seen that the HD and D_2 peaks decrease more rapidly than the H_2 peak. This is consistent with hydrogen diffusing from the bulk and replenishing the surface concentration. The effect becomes much more marked at longer times.[6]

There is, however, a further effect which could contribute to the source of hydrogen. In a system which is insufficiently outgassed, thermal desorption and adsorption will lead to redistribution of gases onto the torus wall facing the plasma from other surfaces in the system. The presence of water vapour in the system is likely to be a factor in this

$$g^n = \frac{T^n - f}{(1-f)T^{n-1}}$$

The value of f is given by T_1. These are plotted in Figure 7 and it can be seen that the diffusive source varies with discharge number with the simple form:

$$g^n = g_o \{1-A\exp(-Bn)\}$$

when $g_o = 0.73$, $B = 0.28$ and $A = 0.8$. Using this value of g^n we obtain the fit of the model to the experimental data as shown in Figure 8.

The model predicts that after a series of discharges in deuterium the equilibrium plasma composition will rise asymptotically to the value:

$$T^\infty \text{ (deuterium)} = \frac{f}{1-g_o(1-f)} = 0.66$$

If we now double the filling pressure, then we expect f to increase to the value of 0.5 to give $T_\infty = 0.8$. These predictions agree very well with the experimental data.

Further, if we increase the time between shots we would expect more hydrogen to diffuse from the bulk of the wall and replace deuterium in the surface layer. This would give rise to an increase in the hydrogen component, as is experimentally observed (Figure 4).

4.4 Change back to hydrogen

When the change is made from deuterium discharges back to hydrogen it is found, as expected, that the deuterium concentration decays in successive discharges. The results for both the Fabry Perot interferometer and the desorption probe are shown in Figure 6. The results from the interferometer are in arbitrary units and have been normalised to the results for the carbon probe. It is observed that the rate of change with the number of discharges is in good agreement between the two techniques.

The decay of hydrogen in successive deuterium discharges and vice versa are compared. It is apparent that the initial decay is the same for both series of discharges. However, for hydrogen the rate of decay is slower after about the first five discharges. On the basis of the model outlined we interpret the initial decay as release of gas implanted

function of incident energy and as ion temperatures increase the component reflected from the walls will fall. The reflection coefficient is also a function of the target atomic number and so the reflected component could be reduced by going to a lower z wall material. The effect of an increased ion temperature on the ion induced release component is not known as there are no relevant experimental results in this energy range. However, the ion induced re-emission could be reduced either by using a wall with a higher diffusion coefficient and thermally desorbing the trapped gas between discharges or by using a reactive metal such as titanium in which the hydrogen can diffuse into the bulk without readily desorbing from the surface.[13] Thus it should be possible to have a quite large degree of control over the recycling behaviour and to reduce it or increase it substantially.

One further aspect of recycling has only been touched on briefly. If there is a large coverage of the surface of the torus with adsorbed molecules containing hydrogen such as CH_4 and H_2O then these will contribute to the effective recycling behaviour. Cross contamination of surfaces exposed to the plasma by other outgassing surfaces between discharges could lead to very slow removal rate of hydrogen from the system when changed to deuterium discharges. We believe from the low Z_{eff} in our discharges and from the mass spectrometry of the residual gases, together with the similarity between the hydrogen and deuterium behaviour, that we have a small contribution to recycling from this effect in DITE.

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$$\alpha\ I_{H\alpha}\ \frac{\int_0^a n_e\ n^H\ (S + C^1)\ rdr}{\int_0^a n_e\ n^H\ X\ rdr}$$

$$\alpha\ \ I_{H\alpha} \text{ for constant plasma conditions}$$

The term $\int \frac{dn^H}{dt}$ will only be appreciable in the ionization phase of the discharge. Hence for all but early times:

$$I_{H\alpha}\ \alpha \text{ Total hydrogen flux entering plasma.}$$

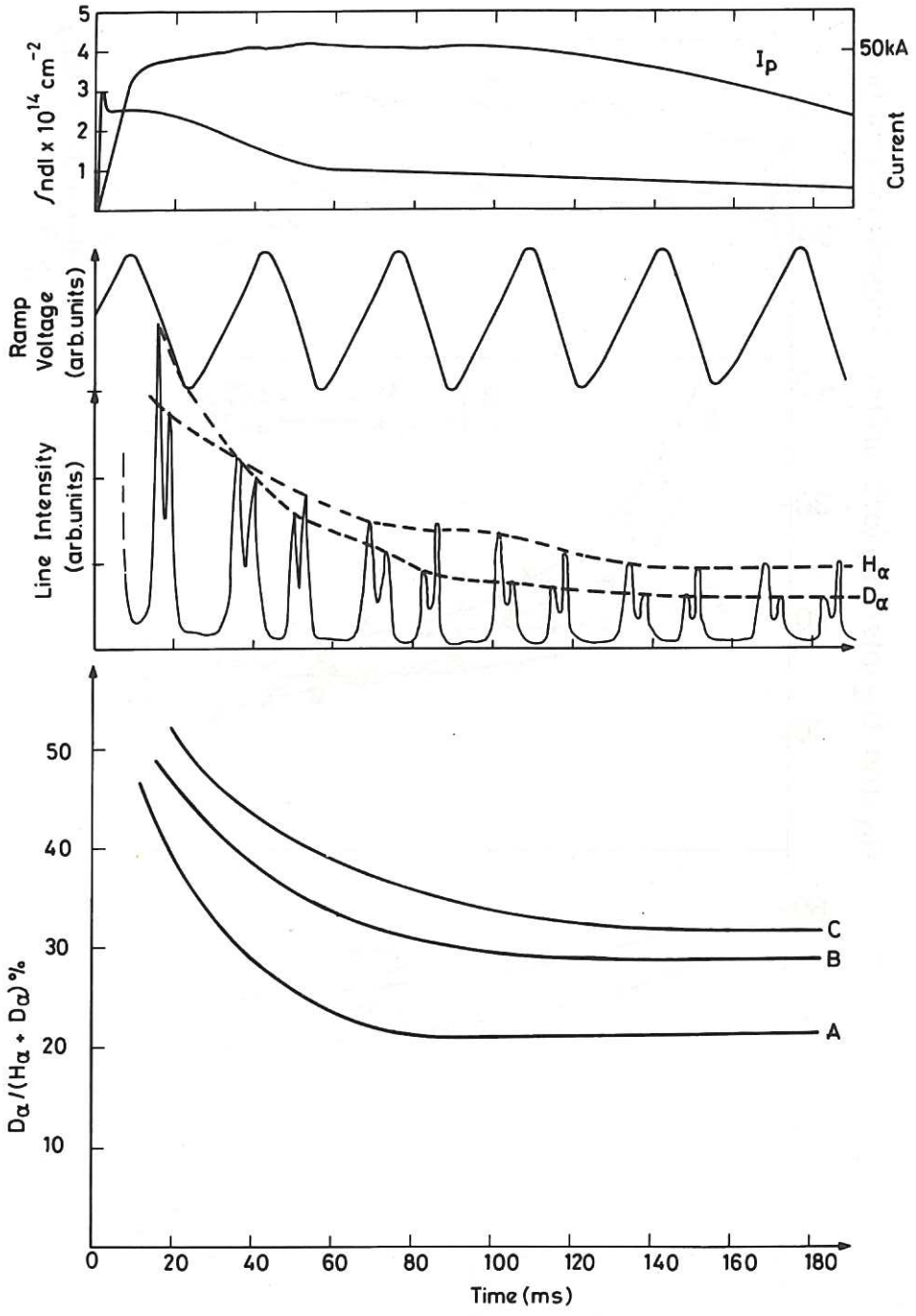

Fig.1 Three 50kA discharges in deuterium following many in hydrogen:
a) Plasma current I_p and line density $\bar{n}_e$.
b) Fabry Perot interferometer ramp voltage and signal intensity.
c) Ratio of deuterium to total emission in the first three discharges A, B and C. D_α corrected for Doppler broadening.

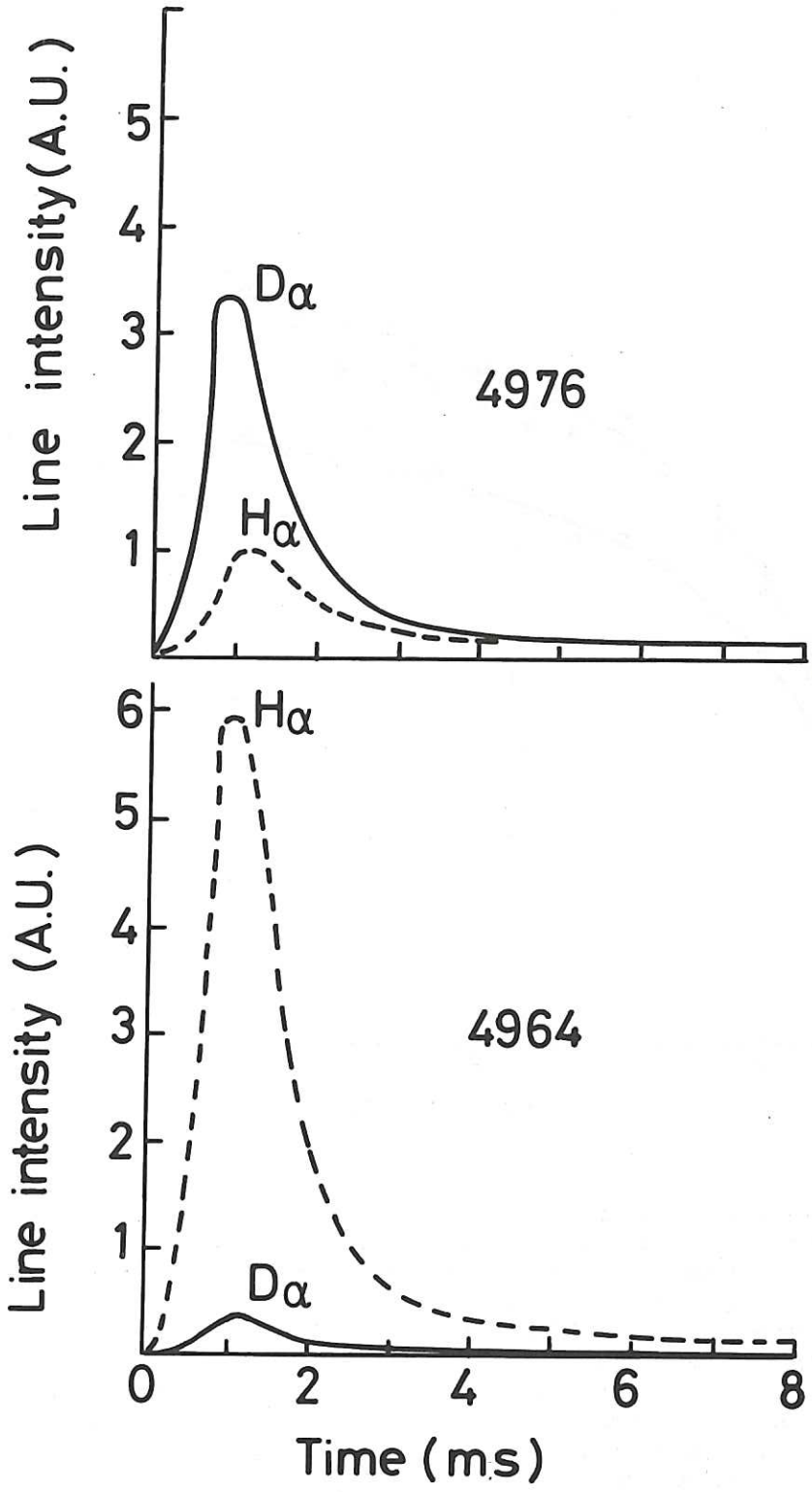

Fig.3 Ionization of H_α and D_α lines measured with the Fabry Perot interferometer:
a) During the first discharge in deuterium.
b) During the first discharge in hydrogen following deuterium discharges – D_α corrected for Doppler broadening.

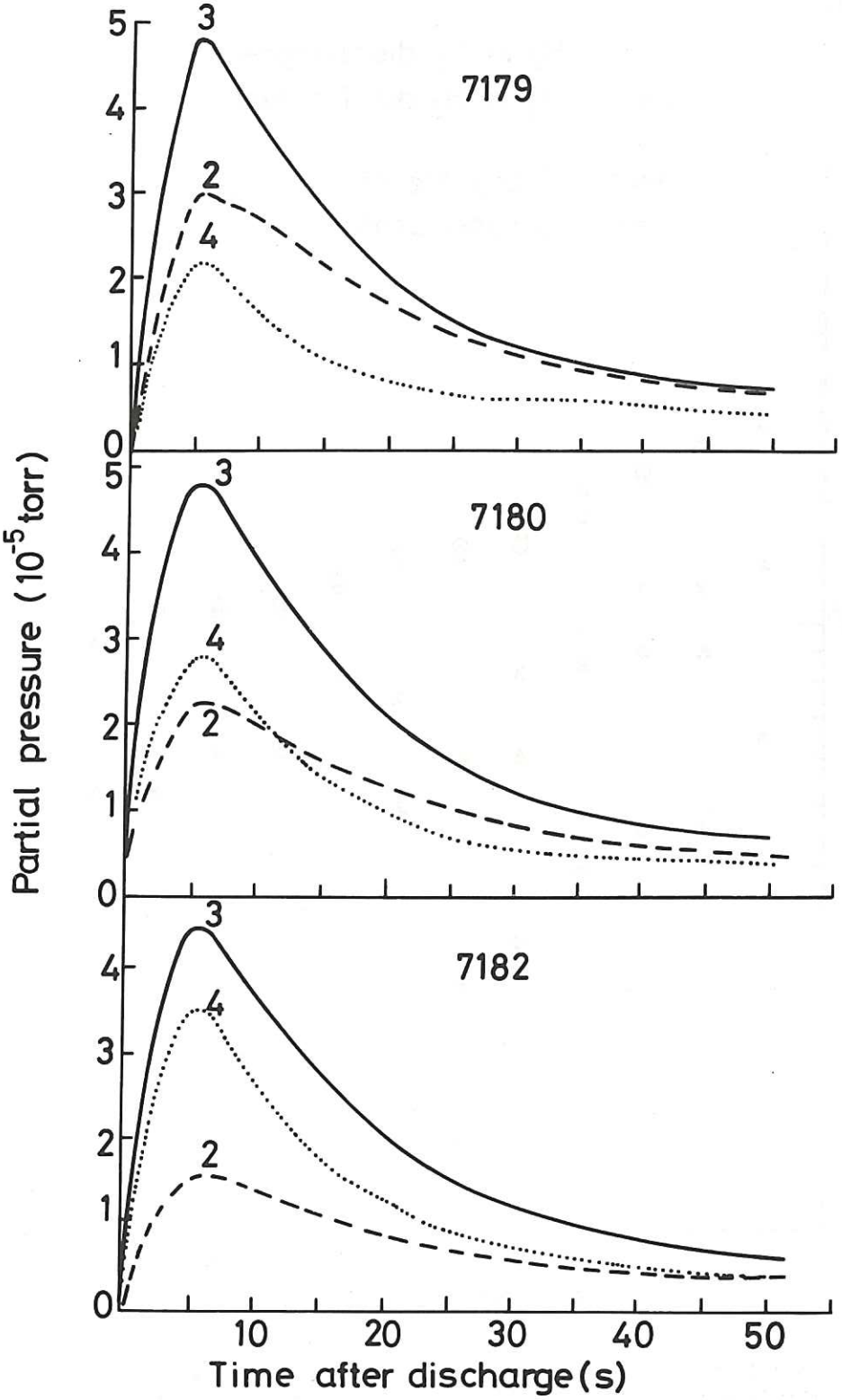

Fig.5 Time dependence of the release of H_2 (mass 2), HD (mass 3) and D_2 (mass 4) after a series of discharges in deuterium. Measurements made with the mass spectrometer:
a) First discharge in D_2
b) Second discharge in D_2
c) Fourth discharge in D_2

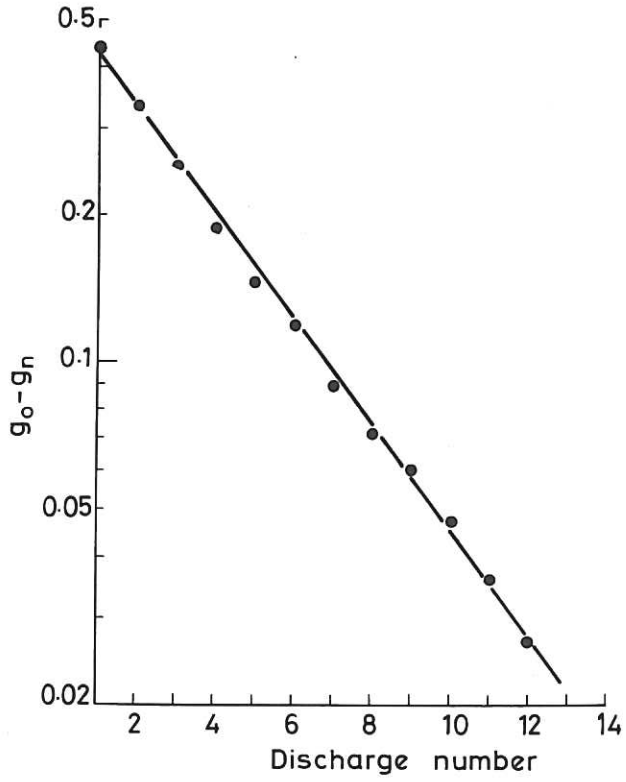

Fig.7 The fraction $(g_o - g_n)$ of the gas in the surface layer which is replaced by hydrogen diffusion from the bulk in successive deuterium discharges. g_o and g_n are defined in Section 4.3

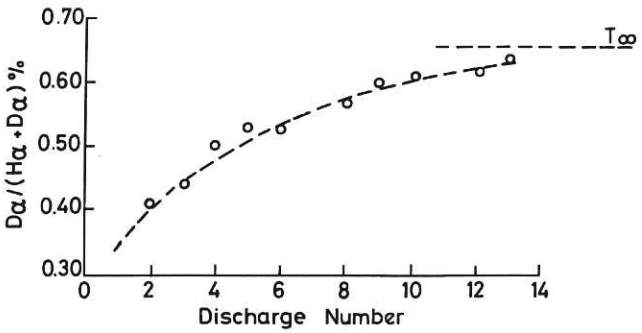

Fig.8 Fabry Perot interferometer measurements of $D_\alpha/(H_\alpha + D_\alpha)$ compared with the model described in Section 4.3