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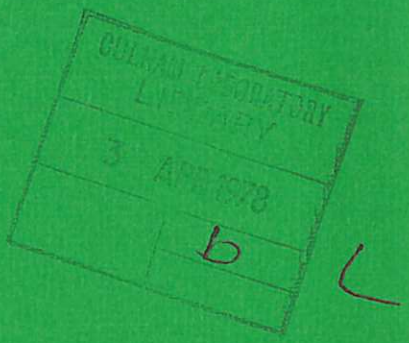

A NOVEL TECHNIQUE FOR MEASUREMENT OF ENERGETIC HYDROGEN FLUX TO THE WALLS IN FUSION DEVICES

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A B S T R A C T

A carbon probe in the form of a small filament has been used in the shadow of the limiter in the DITE tokamak[1] to trap the flux of energetic hydrogen atoms and ions. The trapped particles are released after a discharge by withdrawing the probe into a separate vacuum system and heating the filament. The gas released is measured mass spectrometrically to obtain quantitative information on the incident flux. Some preliminary measurements of flux to the wall and as a function of radial position of the probe are described.

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1. INTRODUCTION

Knowledge of the energetic hydrogen flux to the walls or limiters of large plasma physics experiments is of vital importance for several reasons. Firstly, it provides information on the re-cycling processes. In addition, it facilitates the calculation of sputtering yields, both of wall and limiter material and also of gaseous impurities on the walls. Power loss calculations can be made provided particle energies are known. Looking ahead to fusion reactors, it also has relevance to tritium hold up problems. Nevertheless, few diagnostics are currently in use which allow measurements of this important parameter. Indirect measurements by probe bolometers are made; a more direct method using charge exchange neutral particle analysers has the disadvantage that particles of low energy ($\lesssim$ 150 eV) are not detected.[2]

The technique proposed here is to trap the hydrogen flux in a small probe which represents a section of the wall or a limiter, and to subsequently measure this flux during complete thermal re-emission. Unfortunately the technique is not as simple as it appears at first sight. In many materials, e.g. molybdenum and stainless steel, hydrogen has a high diffusion coefficient at room temperature, resulting in loss of a major part of the incident flux before desorption measurements can be made.[3] In reactive metals, e.g. niobium, a high trapping coefficient can be maintained to high particle doses,[4] but diffusion throughout the material makes complete thermal re-emission difficult. A possible candidate, tungsten, shows little loss of hydrogen at ambient temperatures,[5] but suffers from major loss due to backscattering at low particle energies.

Recent measurements of the trapping of hydrogen ions in a carbon target[6] show this material to have several advantages: a) Low backscattering yield with a trapping efficiency of > 90% at ion energies > 1 keV and $\sim$ 45% even at 10 eV.[7] b) No measureable thermal re-emission at temperatures < 400K. c) High dose trapping capability; up to $\sim 10^{18}$ ions cm^{-2} for 20 keV deuterons. The only minor disadvantage is the loss of hydrogen as methane (CH_4) during thermal re-emission measurements. Ideally methane re-emission should also be recorded, but the loss has been shown to occur in a narrow

band of temperature around 1000K [8] and the fractional loss as checked from a few sample measurements in the DITE tokamak[1] is only ∿ 10%.

Thermal desorption spectrometry can provide some evidence as to the energy of the incident particles, which can be ions from the plasma or charge exchange neutrals. However deconvolution of such spectra is complex, especially when traps or chemical interactions influence the thermal re-emission.[9] Integration of such spectra however gives the total number of particles trapped, from which the incident flux can be determined as discussed in Section 3.

2. EXPERIMENT

The pyrocarbon target material is obtained from Le Carbone, Portslade, Sussex, UK. A probe is cut in the form of a V filament, of cross-section 0.5 x 0.8 mm, with 10 mm arms. Stainless steel and copper support clamps allow D.C. (14 ampere) heating to a maximum temperature of ∿ 1500K, measured initially using a 0.025mm Pt, Pt-13% -Rh thermocouple. Thereafter a programmable ramp generator is used to produce a linear increase of temperature with time. A remotely controlled bellows drive unit, with potentiometric position control, allows an accuracy of ± 2 mm to be obtained in measurement of probe tip position from the centre of the torus. Figure 1 shows a schematic of the system.

A remotely operated U.H.V. gate valve, A, is used to isolate the desorption vacuum chamber from the torus. The desorption chamber is pumped by a large liquid nitrogen cooled titanium sublimation pump, together with a getter ion pump mounted some distance outside the fringing field of the torus. A quadrupole mass spectrometer is used for residual gas analysis in the desorption chamber, in addition to its primary use for recording the hydrogen desorption after a tokamak discharge. A pumping speed of 2.8 ℓs^{-1} has been measured for the desorption chamber. This results in a high sensitivity for measurements of hydrogen desorption rates, however, the low pumping speed leads to a rather high residual gas pressure of 8×10^{-8} Torr after a bake out to ∿ 100°C, mainly because of the large surface area of the bellows. In practice it has been found that adsorption of neutral

hydrogen molecules from the background gas in the torus determines the limit to sensitivity which is $\sim 10^{13}$ atoms cm^{-2}.

The operation of the experiment is as follows. The vacuum system is pumped and baked prior to the introduction of a new carbon filament to the torus. The carbon probe is outgassed at 1500K for 5 minutes, after which the chamber is remotely isolated from the titanium getter pump by closing the small isolation valve, B. The main torus gate valve, A, is then opened, and the probe inserted to $\sim$ 28 cm minor radius. A test cycle, without plasma but with injection of working gas, provides a background hydrogen adsorption on the probe. The total exposure amounts to $\sim 10^{-3}$ Torr seconds of hydrogen on average. The gate valve, A, closes automatically when the probe is withdrawn to the desorption position, after which the small isolation valve, B, is opened.

The hydrogen release rate is recorded as a function of carbon probe temperature over a period of $\sim$ 90 seconds, after which 1300K is reached and all hydrogen previously adsorbed onto the surface is released. The area beneath the peaks in the desorption spectra is proportional to the amount of adsorbed hydrogen. The amount of gas desorbed from a run without plasma is $\sim 10^{13}$ atoms cm^{-2} and this is subtracted from similar measurements made during tokamak discharges, when energetic ions and atoms are trapped in the carbon with a range distribution extending up to several tens of Å below the surface, dependent on the discharge conditions.

Calibration of the quadrupole is made normally twice each day, using the fast gas injection facility to introduce the working gas(es) to the desorption chamber, with the gate valve open. Calibration is against the B.A. ion gauge, the sensitivity of which is known for hydrogen. This is located near to the quadrupole ion source. Little variation in system sensitivity over a period of a few days is observed.

3. THEORETICAL CONSIDERATIONS

It has been demonstrated, by plotting experimental results from a number of different ion-target trapping measurements, that a

universal curve exists for the reflection coefficient when plotted as a function of the reduced ion energy.[7] From this curve the trapping efficiencies for 10 eV and 1 keV hydrogen ions in carbon are expected to be $\eta \approx 45\%$ and $\eta > 90\%$ respectively. The chemical bond which forms is strong enough to prevent any diffusive loss, at least for temperatures below $\sim$ 400K.[6]

However hydrogen loss does occur as the particle dose to the target increases, due to ion induced re-emission or 'gas sputtering'. Eventually a condition is reached where the target saturates and trapping and re-emission rates become equal. For 20 keV deuterons in carbon, for example, this saturation number N_{SAT} has been measured to be 2.3×10^{18} atoms cm^{-2} trapped.[6] A lower ion energy will, of course, result in a lower value for N_{SAT} due to the shorter ion range.

Considering ion induced re-emission as a loss mechanism in the carbon probe, and assuming that a fraction (1-f) of particles in the target are lost per discharge due to this mechanism we have:

Number trapped after the first discharge = $\eta N_1 f$

After second discharge = $(\eta N_1 f)f + \eta N_1 f$

$$\text{After mth discharge} = \eta N_1 f \left(\frac{1-f^m}{1-f}\right) \qquad (1)$$

Where N_1 is the number of particles incident per unit area per tokamak discharge. Note that f is dependent on N_1.

The maximum concentration in the ion range, as $m \to \infty$ is therefore:

$$N_{SAT} = \frac{\eta N_1 f}{1-f} \quad cm^{-2} \qquad (2)$$

It is useful to compare this model with the corresponding one for the case of a surface continuously bombarded by an incident flux J_o when the desorption cross section is σ. The concentration, n, within the ion range is given by:

$$\frac{dn}{dt} = J_o \eta - J_o \sigma n \qquad (3)$$

assuming n = o for t = o, the solution is:

$$n = \frac{\eta}{\sigma} \left(1 - \exp(-J_o \sigma t)\right) \qquad (4)$$

Then as $t \to \infty$,

$$N_{SAT} \to \frac{\eta}{\sigma} \tag{5}$$

By comparing expressions for the pulsed and steady state cases we obtain:

$$f = \frac{1}{1 + \sigma N_1} \tag{6}$$

where $N_1 = J_o t_1$ and t_1 is the pulse length.

Cumulative experiments in which the carbon probe is withdrawn and heated after 1, 2 and 3 etc discharges are therefore essential for determination of the loss fraction (1-f) and hence the incident number of particles N_1.

In addition, the maximum concentration in the particle range, N_{SAT}, is related to the particle energy. In tokamaks the flux of atoms and ions impinging on walls and plasma limiters has of course a distribution of energies. An accurate measure of N_{SAT} would relate to the MAXIMUM particle energy, but would require measurement over many discharges especially if the distribution had a long high energy tail. Measurements over a few discharges using equation (2) would relate to a mean effective particle energy which determines the magnitude of the gas sputtering process.

Measurements have been made of the saturation number N_{SAT} for carbon and stainless steel targets at high energies.[10] It is hoped to extend these to lower energies and by comparing with values of N_{SAT} measured in the tokamak to obtain an estimate of the mean energy of the incident hydrogen ions and atoms.

4. RESULTS AND DISCUSSION

4.1 Cumulative discharges

A typical set of thermal desorption spectra are shown in Figure 2, in this case taken from a series of similar discharges with the carbon probe fixed at 28 cm minor radius. This position is 1 cm outside that of the fixed limiter, the diaphragm which

determines the plasma diameter. The form of the re-emission with increasing carbon temperature is similar to that observed previously using 20 keV hydrogen ion bombardments of electrocarbon.[6] However, the major peak is shifted to slightly lower temperatures and some structure is discernable on each side of the peak suggesting release from sites of different activation energy. These differences are almost certainly due to the lower energy incident particles, and possibly the different type of carbon used for probe material.

The important results from Figure 2 are obtained by integration of each spectrum. This gives the total amount of gas desorbed after each exposure to one, or a series of discharges. The experimental measurements are plotted as circles in Figure 3, as a function of number of discharges. The four crosses give the best fit to the stepwise solution. Clearly the experimental results fit the models suggested for gas sputtering very well indeed, and give confidence in calculations of parameters such as N_1 and σ.

From this curve it can be deduced directly that:

$$\eta N_1 f = 8 \times 10^{14} \text{ cm}^{-2}, \text{ and } \eta N_1 f(1+f) = 1.45 \times 10^{15} \text{ cm}^{-2}$$

Hence $f = 0.8$

Also $N_{SAT} = \frac{\eta}{\sigma} = \frac{8 \times 10^{14}}{0.2} = 4 \times 10^{15} \text{ cm}^{-2}$ from equation (2), or

$\sigma = \eta\ 2.5 \times 10^{-16} \text{ cm}^2$.

If a value for η of 0.5 is taken from the universal η-ε curve, i.e. corresponding to an ion temperature $\sim$ 50 eV near the wall, then:

$$\sigma = 1.25 \times 10^{-16} \text{ cm}^2$$

A similar figure has been deduced independently for stainless steel during H-D recycling studies from the torus wall using a mass spectrometer.[11]

The value of N_1 is therefore:

$$N_1 = 2 \times 10^{15} \text{ cm}^{-2} = J_o t$$

The average flux over a 50 kA discharge (∿ 150 ms) at 28 cm is therefore:

$$J_o = 1.3 \times 10^{16} \text{ particles cm}^{-2} \text{ s}^{-1}$$

4.2 Radial variation of particle flux

In the following experiments the particles trapped in the carbon probe are plotted as a function of probe radial distance from the plasma centre.

Results are shown in Figure 4, for 100 kA discharges with a 10 cm diameter probe limiter at 18 cm minor radius. A further set of data is presented in Figure 5 for 50 kA discharges, the probe limiter in this case at 26 cm and the divertor on. In each case the hydrogen flux increases rapidly at radii less than 29 cm. Since the fixed limiters are at 27 cm this indicates a significant particle flux in their shadow. The small increase at 32-33 cm minor radius have been observed during each series of experiments in which the probe position was moved through the gate valve, and is probably due to the shadowing effect of the port. The wall of the torus is at a radius of 31 cm. The flux observed outside 31 cm must be due to charge exchange neutrals only, and the decrease with radius is thus a simple geometrical effect.

An absolute value for the flux to the wall (radius 31 cm) can be estimated from the figures deduced for σ and f from cumulative discharge data. For the 50 kA discharges shown in Figure 5 this flux is $J_o \approx 4 \times 10^{15}$ particles cm^{-2} s^{-1}, assuming that the flux is constant during a discharge of duration 150 ms.

Unfortunately the form of the curves in Figures 4 and 5 at radial distances << 28 cm minor radius is not representative of the incoming flux due to a decrease in the fraction retained in the probe, f, with increasing flux density. The effect of ion induced release has been deduced in Section 3, (equation 6), and is plotted in Figure 6. We

have estimated that the trapping coefficient, η, is approximately 0.5. At 28 cm minor radius the carbon probe further underestimates the flux by 20% due to ion induced re-emission, i.e. $f = 0.8$. Thus the measured flux has to be corrected by a factor 2.5. At smaller radial positions the loss fraction (1-f) will be much higher. Clearly cumulative discharge measurements at each radial position are required before much can be said about the flux inside the fixed limiter position.

The results from the carbon probe have been compared with the flux measured using a Neutral Particle Analyser,[12] (NPA). The NPA however only measures neutrals with energies above 100 eV. Calculations of measurements using a 100 kA plasma at $\sim$ 64 ms after the start of a discharge show this flux to be $\sim 3 \times 10^{16}$ neutrals s^{-1} $Sr^{-1}cm^{-2}$. The results from the carbon probe under the same conditions, Figure 4, give a flux at the wall (a = 0.3 m) corrected for backscattering and the solid angle subtended by the plasma to the probe of 5×10^{15} neutrals s^{-1} Sr^{-1} cm^{-2}. This assumes that the flux is constant throughout the pulse length of 0.12s. The lower energy limit of the NPA would be expected to result in a measurement of about 50% of the total neutral flux on the basis of the measured neutral particle temperature. Thus the carbon probe appears to be measuring about an order of magnitude less neutrals than the NPA. Further investigation of this discrepancy between the two techniques is required.

At smaller radii a comparison can be made between the flux expected from the data on plasma temperature and density,[13] again with the standard limiter at 18 cm. From kinetic theory this flux is $\frac{1}{4} n\bar{c}$, and the mean velocity $\bar{c}$ has been calculated from the ion sound speed. On this basis good agreement has been obtained with the energy flux to the wall.[14] At 24 cm minor radius the calculated flux is $J_o = 1.5 \times 10^{18}$ particles $cm^{-2}s^{-1}$, ($n_e = 1.2 \times 10^{18}$ m^{-3}, T_e = 10 eV) as compared with the uncorrected carbon probe measurement (Figure 4) of $\sim 6 \times 10^{16}$ particles cm^{-2} s^{-1}. This yields a measured value for the fraction in the carbon of $f = 0.08$, assuming $\eta = 0.5$ as previously. Referring to equation (7) we see that for a value of $J_o = 1.5 \times 10^{18}$ cm^{-2} s^{-1} we would expect $f = 0.03$. Considering the extrapolation involved this is in reasonable agreement with our directly measured value of f.

4.3 Recycling in hydrogen and deuterium discharges

The carbon probe has also been used with considerable success for investigations of hydrogen - deuterium recycling. By scanning the mass spectrometer during thermal desorption of the gas in the probe it is possible to measure the amount of each component, hydrogen and deuterium implanted during a discharge. The hydrogen release from the torus wall and limiters was studied when the working gas was changed to deuterium. Ion trapping and particle induced release were shown to play an important role in the recycling process, as was hydrogen diffusion from the bulk in the stainless steel torus wall. Measurements using a Fabry Perot interferometer showed excellent agreement with the carbon probe results. An example of the type of data obtainable using the carbon probe for recycling measurements is shown in Figure 7. Here the quadrupole mass spectrometer is used to scan the mass range 1 to 5 during thermal desorption and the variation in gas release rates of H_2, HD and D_2 are recorded. The HD molecule is formed by isotopic exchange at the surface. The total amounts of hydrogen and deuterium released can be deduced from integration of the three spectra. The recycling measurements are described in detail in a separate publication.[11]

5. CONCLUSIONS

Although the carbon probe has been operational in the DITE tokamak for a relatively short period of time, it has already demonstrated itself as a valuable diagnostic tool for the study of particle flux to the torus wall and the outermost regions of the plasma.

For a series of 50 kA discharges, in which the divertor was operational, a figure for the particle flux to the wall of $\sim$ 4 x 10^{15} particles cm^{-2} s^{-1} has been measured. The experimental results obtained during cumulative discharge measurements show a good fit to the theoretical model proposed for ion induced gas release from the carbon probe. Provided some experimental measurements on low energy (100 eV to 5 keV) hydrogen ion trapping in carbon are forthcoming, in particular the saturation number N_{SAT} as a function of ion energy, then it seems possible that information on particle energy to the DITE torus can also be obtained using the carbon probe technique.

Clearly much more information can be obtained from the carbon probe in its present form, for instance, investigation of the effectiveness of divertor and limiters in reducing the flux to the wall, and the effects of plasma parameters such as plasma current and density on this flux. However the simple technique does have its limitations, as only an integrated picture of the processes occurring during the discharge is obtained. At the present time a new carbon probe experiment is under construction to allow time resolution of the particle flux. This entails the use of a segmented carbon disc which rotates during the discharge, rather than a single carbon filament. A window exposes each segment for a short period ($\sim$ 10 ms) prior to removal and subsequent thermal desorption.

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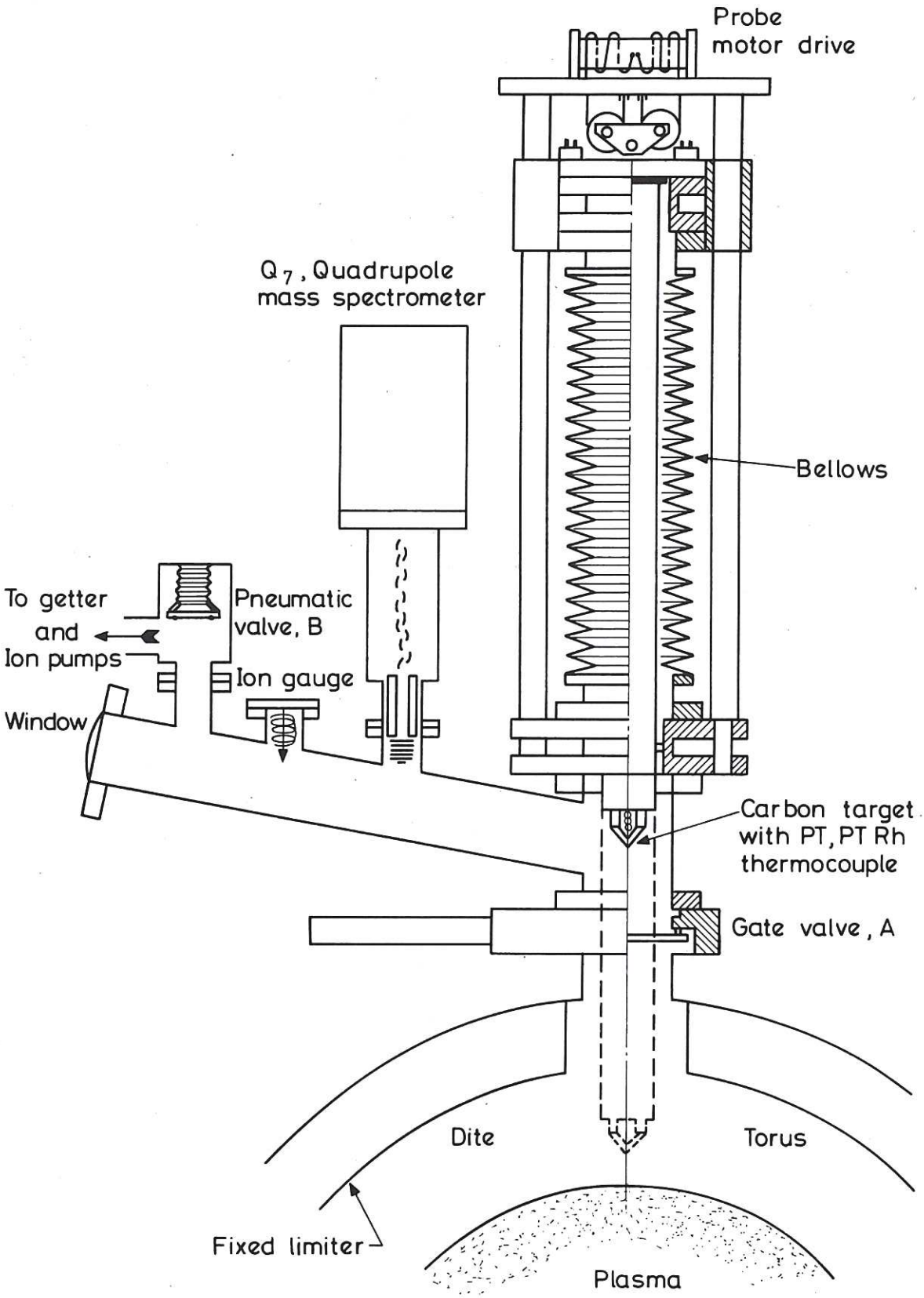

Fig.1 Schematic diagram of the carbon probe assembly mounted on the DITE torus.

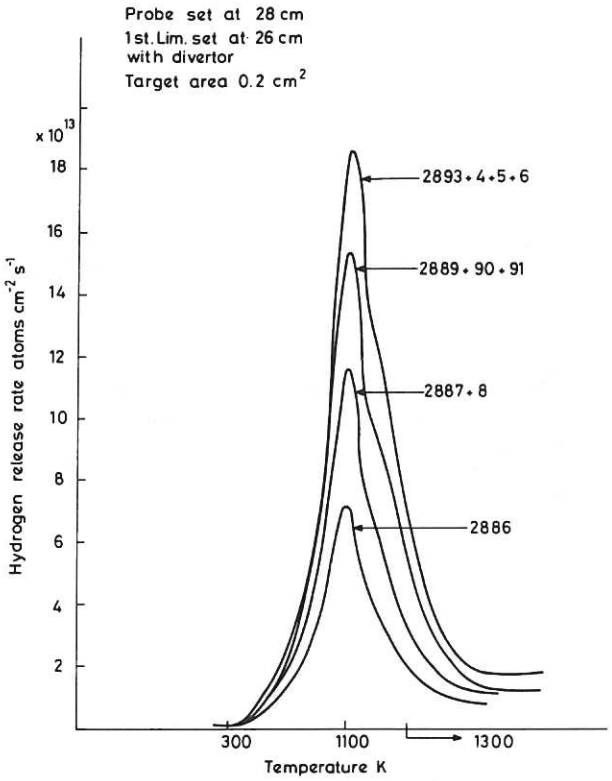

Fig.2 Hydrogen release spectra from the carbon probe following 1 to 4 cumulative discharges.

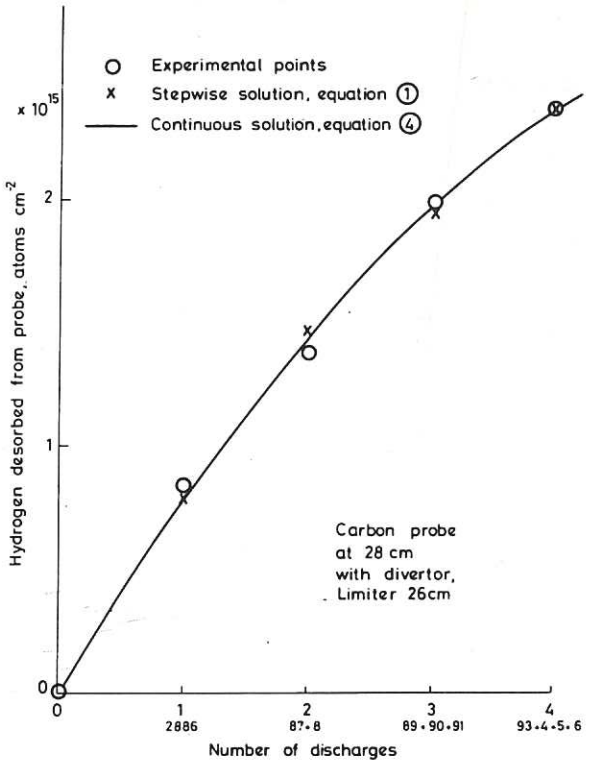

Fig.3 Fitting of each theoretical treatment of ion induced release to the experimental data.

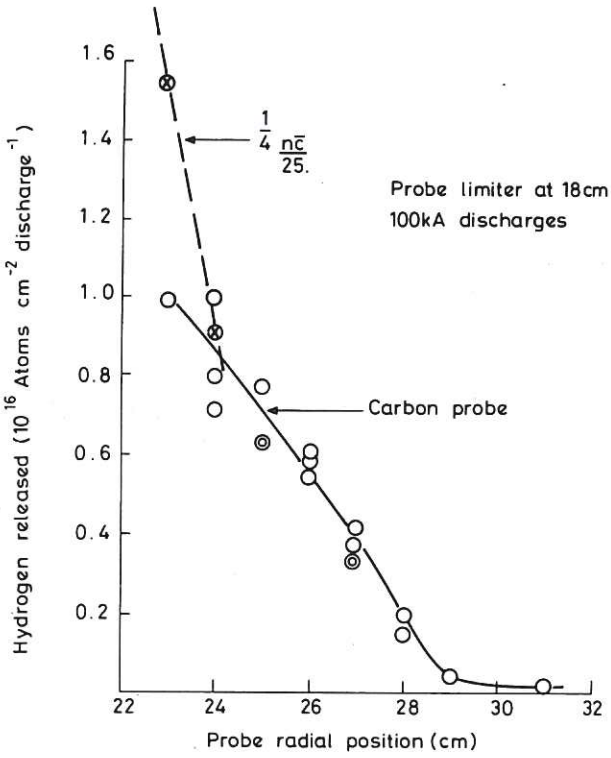

Fig.4 Variation in amount of hydrogen desorbed with radial distance of the carbon probe from the centre of the torus (small radii).

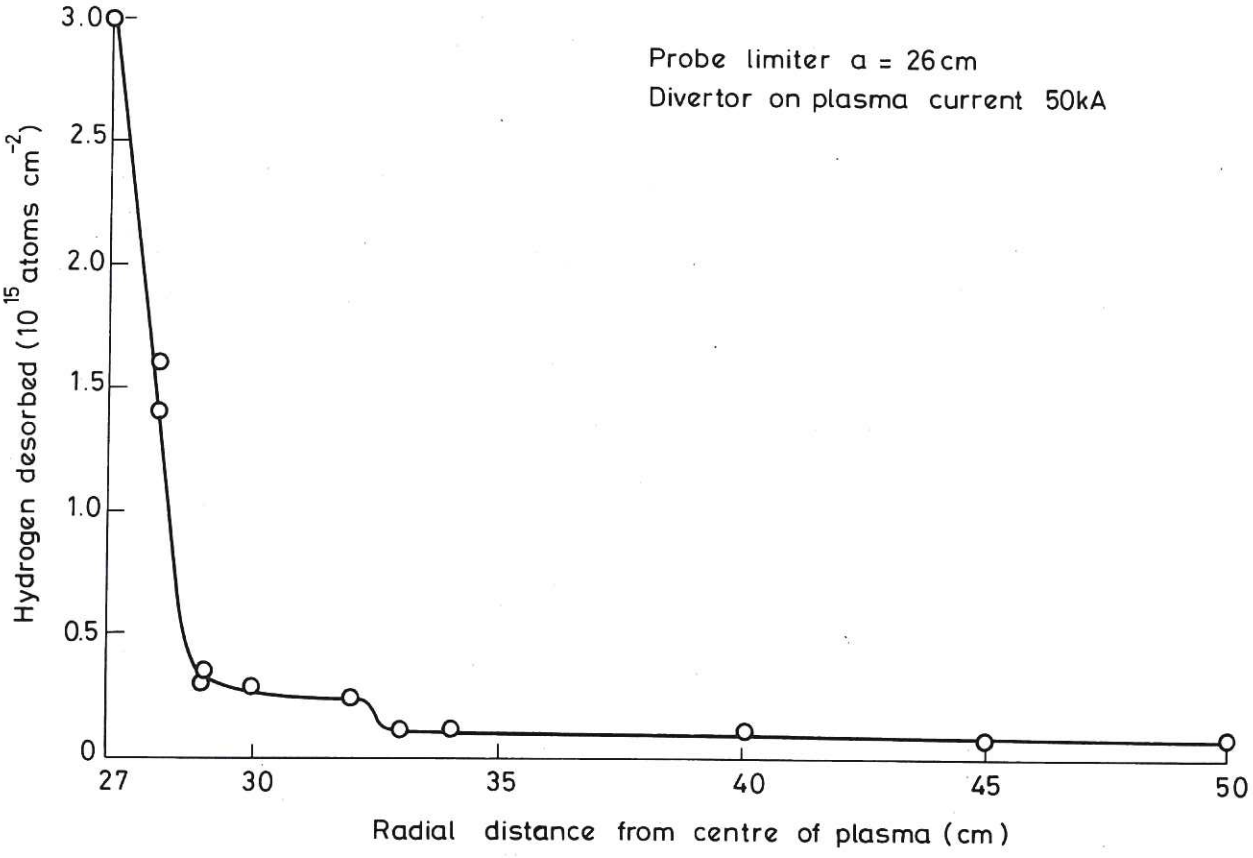

Fig.5 Variation in amount of hydrogen desorbed with radial distance of the carbon probe from the centre of the torus (large radii).

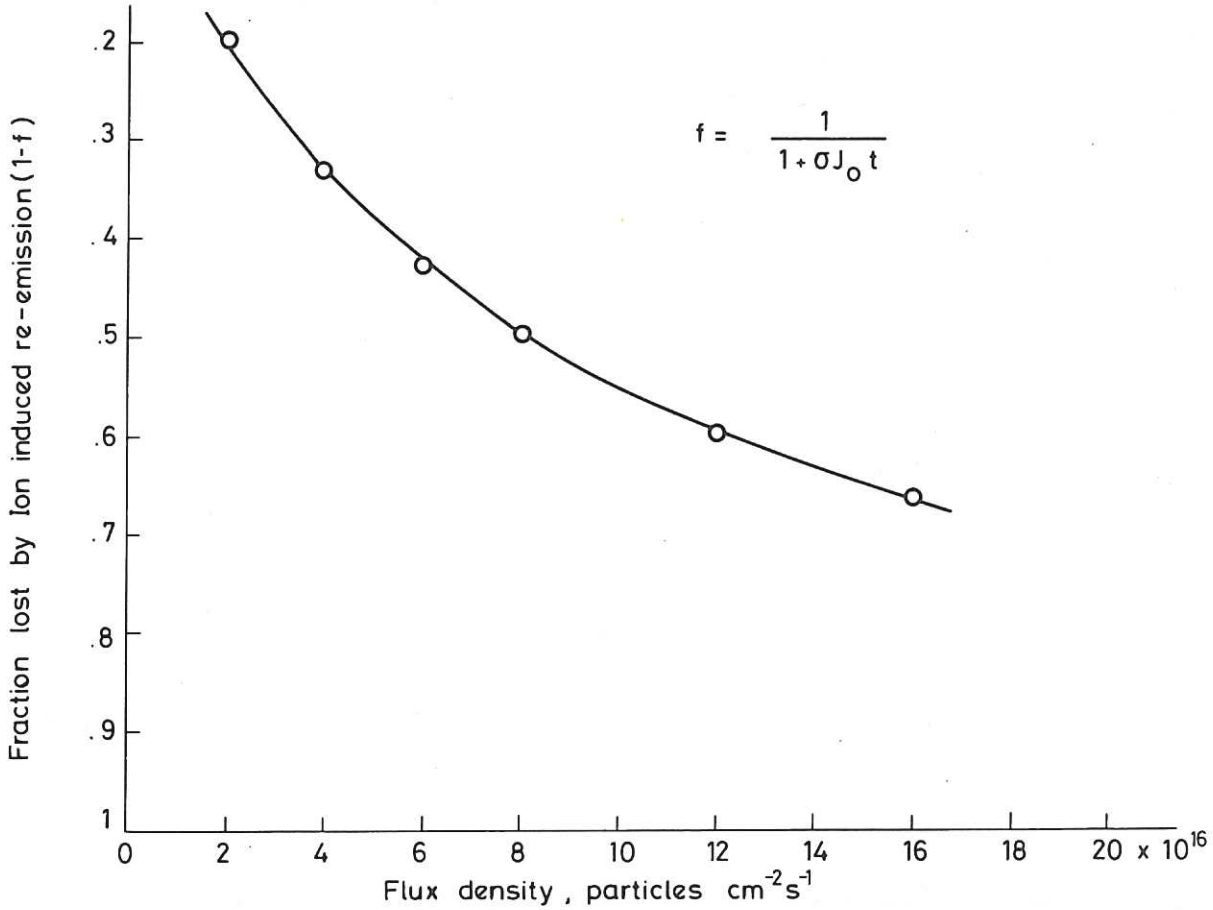

Fig.6 Theory for the loss fraction (1-f) as a function of the incident flux density (1st Point known).

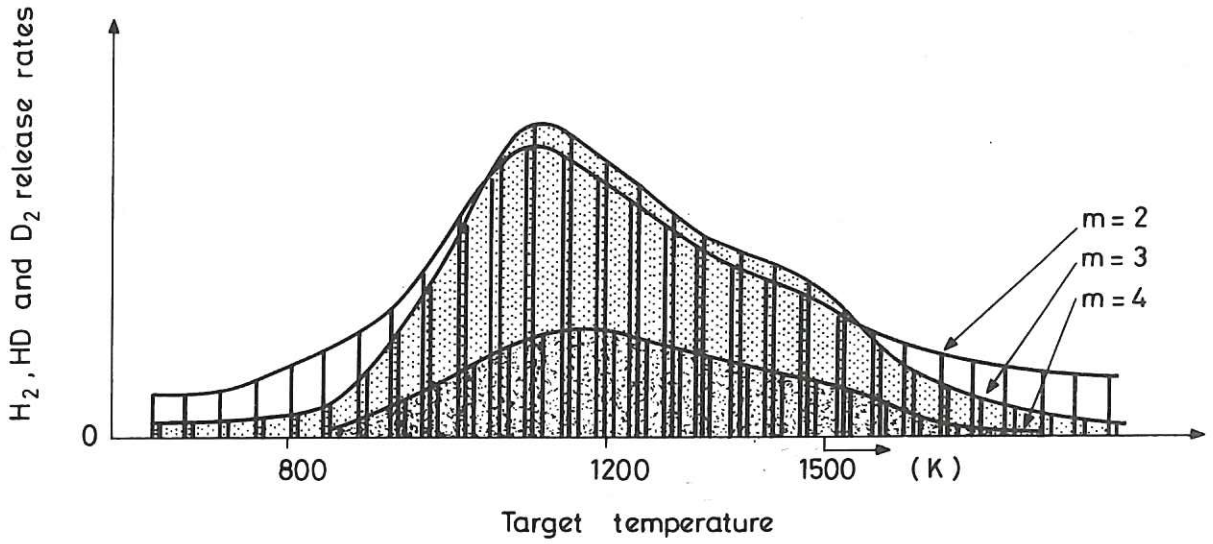

Fig.7 Thermal desorption results from the carbon probe using the quadrupole mass spectrometer in the scanning mode, during recycling measurements.