TRITIUM ENRICHMENT IN THE JET DIVERTOR AND ITS RELATION TO TRITIUM UPTAKE AND RETENTION

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ABSTRACT

Future fusion reactors, like ITER, will rely on an active exhaust system to pump tritium (T) in the divertor and then recirculate it to the fuel stream. Estimation of the T inventory requires a detailed T balance, which determines if T is preferentially enriched relative to D in its pathway from the main plasma to the divertor and pump. On the Joint European Torus (JET), the neutral T concentration in the sub-divertor (pumping plenum and region below the divertor strike point plate) is measured with a modified Penning gauge coupled to a high-resolution spectrometer. In addition, T concentration measurements are made in the plasma edge and strike point region with a spectrometer viewing these regions. The sub-divertor and divertor (region above the strike point plate) T concentration measurements show differences during initial T uptake and retention which are characteristic of wall deposition properties. Since wall retention is one of the factors in calculating the eventual T inventory in a reactor, a detailed study of this process has been undertaken.

I. INTRODUCTION

Recent D-T experiments on TFTR[1] and JET have provided an opportunity to study the link between edge plasma and wall conditions. The D-T isotopic inventory in the walls of a tokamak is important since the hydrogen isotopes fueling the discharge will exchange with those in the wall. This dynamic inventory ultimately controls the D-T fueling behavior within a single discharge and in particular determines the D-T isotopic composition. In addition, if the tritium retention in the wall continues to grow, this can have profound consequences for the safety and environmental acceptability of future fusion reactors.

This paper describes the tritium uptake and retention by the graphite walls of JET during a sequence of pulses (41677-41685) where 100 % T gas is injected into the JET vacuum vessel and in the first shot (41677) the walls were loaded with 100 % deuterium. The purpose of the study is to evaluate wall retention models, using reasonable estimates of implantation fluxes and energies to the surfaces in the T uptake sequence. For this purpose, data from the sub-divertor T concentration measurement (Penning gauge), and, especially, the systematic differences between Penning measurements and the composition measured at the strike point by divertor spectroscopy are sensitive to the tritium saturation of the near divertor wall region. Modeling of these experiments is performed with the neutral transport code: EIRENE[2] to obtain deposition profiles of D and T, which are then supplied as input to the WDIFFUSE[3] wall diffusion model to estimate the divertor wall tritium saturation.

The study proceeds by first examining the dynamics of the discharges in the sequence, and then tracing the evolution of strike point and sub-divertor concentrations over the first four T uptake discharges where the T concentration changes the most. The EIRENE code is used to determine the relation between the strike point and sub-divertor parameters, as a function of wall status. Using these results, we can infer the time evolution of the wall recycling coefficients. Finally, the inferred recycling coefficient evolution is used to test wall implantation and retention models.

II. EXPERIMENTAL ARRANGEMENT

The Penning gauge system for measuring the T concentration in the sub-divertor region of JET is installed at the end of a 2.5 meter vacuum duct on the JET MkII divertor (see Fig. 1). The deuterium, tritium, and other impurity species found in the divertor travel along the vacuum duct to the Penning gauge and are ionized by the Penning discharge. The details of the Penning diagnostic can be found in Ref. 4. The hydrogen Balmer transitions (H_α - 6562.79 Å, D_α - 6561.03 Å, T_α - 6560.44 Å) emitted by the discharge in the Penning gauge are viewed via a quartz fiber and transferred 80 meters to a high-resolution spectrometer.

The hydrogen transitions are easily separated and are analyzed to deduce the sub-divertor tritium concentration. The tritium concentration is also measured via a divertor spectrometer (equipped with polarizing filters) which views the outer strike point region of the divertor (see Fig. 1). The multi-species (D, T, D_2, DT, T_2) EIRENE[1] neutral transport code is used to calculate the spatial distribution of charge-exchange fluxes and energies to the wall area surrounding the strike points. The EIRENE

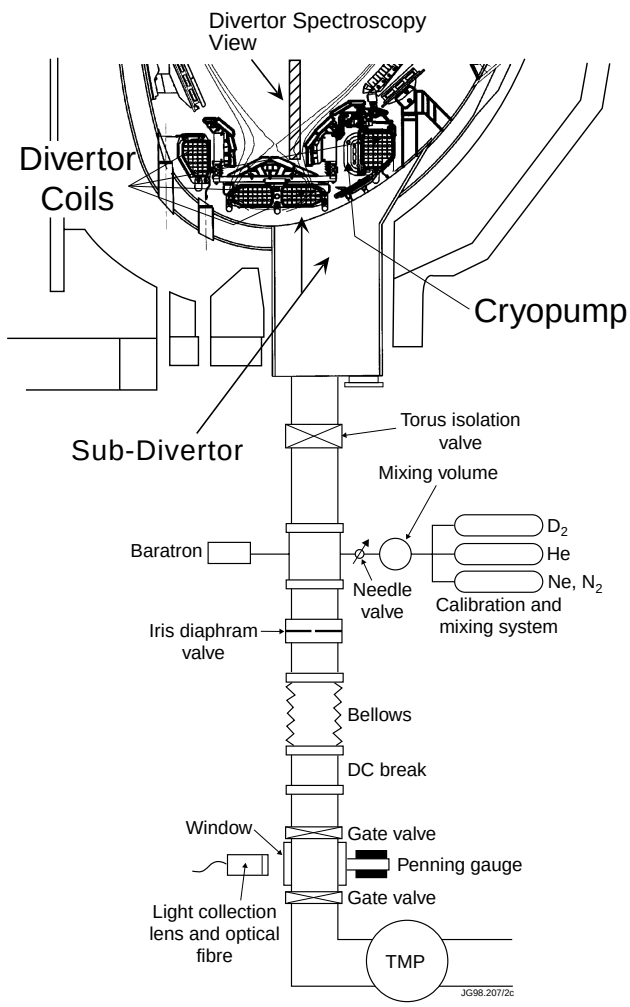

Fig. 1 Penning gauge system for tritium concentration measurements in the JET divertor. The sight line into the divertor is also shown for the tritium concentration measurement via divertor spectroscopy.

calculations use measured divertor strike point plasma parameters to calculate the resulting sub-divertor molecular composition (measured by the Penning gauge). Differences between the T concentration measured by the Penning gauge and divertor spectroscopy are due to the evolution of the species composition of the wall recycling coefficients as the initially deuterium-rich walls become tritium-rich.

Primary emphasis is placed on validating the JET Preliminary Tritium Experiment (PTE) model[5], which inferred fundamental surface coefficients (volume recombination rate, trapping rates) by an empirical fit to post-shot T decay over many shots. Since the primary mechanism active in the uptake experiments (particle-induced detrapping) does not play a role in the post-shot pressure decay measurements which led to the PTE model coefficients, it is of interest to see whether these coefficients provide a reasonable description of the T uptake sequence.

III. TRITIUM UPTAKE EXPERIMENTS

Figure 2 shows measured T concentrations as a function of time after pure T gas is injected in the first discharge of the T uptake experiment (41677), as given by divertor spectroscopy and by the sub-divertor Penning gauge. Before this discharge only deuterium has been exposed to the tokamak walls. The difference in the T concentration between these two diagnostics is expected. The sub-divertor gauge sees only molecules which have undergone several wall impact/reflection/re-emission events. Because the direct flux from the strike point is strongly attenuated with distance, previously D-saturated areas closest to the strike point are the first to saturate with T, then followed by surfaces in the sub-divertor. The energy of the impacting particles is reduced from plasma thermal (near the strike point) to ambient thermal in the subdivertor. When molecules are exchanged from a previously D-saturated surface, D_2 molecules will emerge when T impacts, at least in the initial stages of T uptake.

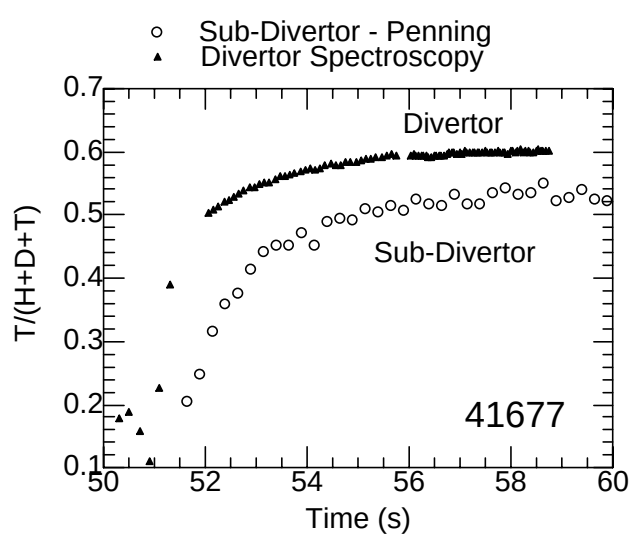

Fig. 2. Comparison of T concentration in the sub-divertor and divertor versus time of the first tritium fueled discharge with 100 % D loaded walls.

As the T input increases, T_2 and DT are also exchanged as well as D_2, and the observed Penning gauge tritium concentration will rise. Thus, (1) the sub-divertor T_2 concentration can be expected to lag the strike point value during these uptake experiments, as is seen, and (2) the degree of this difference is sensitive to the wall condition.

The dynamics of the succeeding discharges in the uptake sequence are similar. Fig. 3(a) shows the variation of the T concentration (Penning gauge) for the sequence 41677-85 in terms of accumulated time. The decay in the T concentration for each shot is due to the termination of the T fueling during the shot. For the analysis of these discharges, co-deposition and bulk diffusive processes are neglected. These processes are significant and eventually dominate the long-term retention of T. The role of T storage in co-deposited layers for JET is treated in Ref. 6.

IV. EIRENE CALCULATIONS

The EIRENE neutral transport code can be used to determine the relationship between the strike point T concentration, the sub-divertor T concentration, and the wall hydrogen concentration. Given (a) the strike point concentration of the impinging ion flux, and (b) an assumed spatial distribution of wall recycling coefficients for D and T, the sub-divertor concentration can be determined. Thus, a time-independent relation between T strike point concentration, C_{sp}, the sub-divertor concentration, C_{sd}, and wall recycling coefficient (R_{wall}) can be determined using EIRENE. Once this relationship has been determined, we can return to the time-dependent data discussed above, and infer the time dependence of the wall state which is disclosed by the experimental data. The rate at which this recycling state is reached is a sensitive test of the component data in the wall models.

This calculation uses experimentally measured divertor strike point profiles[7] of n_e and T_e in the period from 50-60s. Using the measured strike point n_e profile, the D^+ strike-point concentration is varied from 5% to 95% (while the T^+ concentration is varied from 95% to 5%). For each of these values of strike point concentration, EIRENE cases were run with wall re-emission coefficients for D varying from 0% to 100%. Correspondingly, the T and DT recycling coefficients were varied between 100% and 0%. A database of 48 cases was established relating the strike point concentration, the sub-divertor concentration, and the species dependence of the wall recycling coefficient.

The calculated relationship is shown in Fig. 4. The sub-divertor T concentration (C_{sd}) is shown as a function of the global T recycling coefficient, R_T (probability of re-emission of T), with the strike point concentration for each case as a parameter. Using these data, an upper and lower estimate of the sub-divertor concentration as a function of the recycling coefficient can be obtained. The upper and lower values represent the maximum range due to variation of the strike point composition between 5 % and 95 %. Using the measured sub-divertor concentrations the relation shown in Fig. 4 can then be used to obtain $R_T(t)$. The results are shown in Fig. 3(b) for discharges 41677-85. Since various wall models will predict differing rates for reaching a specific level of T wall saturation, the difference between calculated and observed $R_T(t)$ provides a method of validating various wall models.

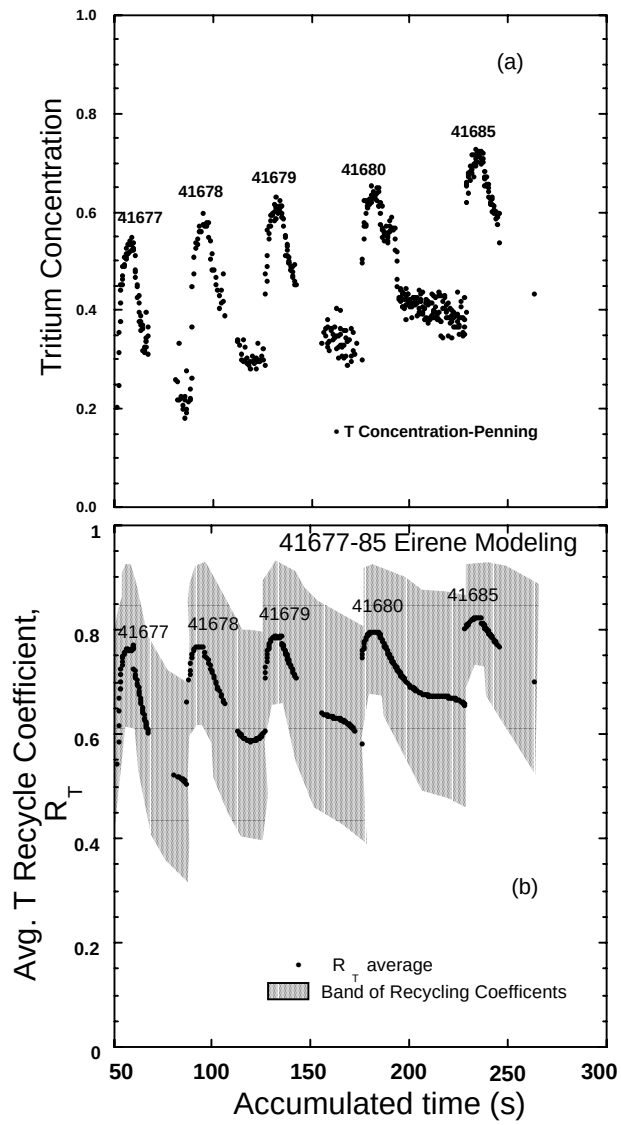

Fig. 3 (a) T concentration measured in the sub-divertor versus accumulated time. (b) EIRENE calculation of the T recycling coefficient, with upper/lower limits due to the strike point concentration variation .

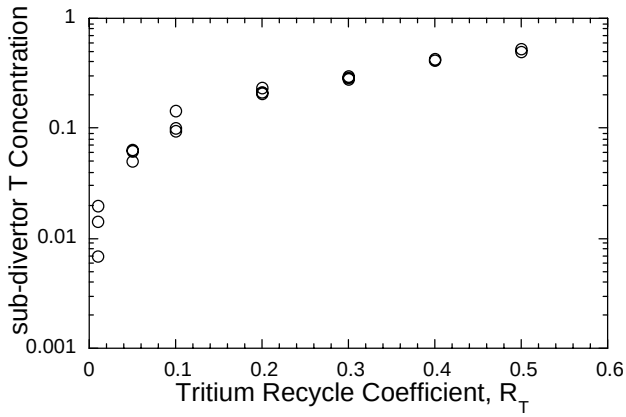

Fig. 4 Calculated (EIRENE) dependence of sub-divertor T concentration on wall recycling coefficient with strike point T concentration varied from 0.05 to 0.95.

V. SPATIAL DEPENDENCE OF IMPLANTATION FLUX AND ENERGY

While the divertor strike point receives the highest flux, the species composition of this region equilibrates very quickly with the flux from the plasma core. The approach to T saturation, starting from $R_T \bullet 0$, depends on the degree of saturation of the wall near the strike point region where the charge exchange (CX) flux is highest. The spatial dependence of the CX flux and energy in this region is therefore needed.

The EIRENE calculations show that the neutral flux is largest near the divertor strike points, > 10^{22} m^{-2} s^{-1}, falling to < 10^{20} m^{-2} s^{-1} in the top half of the vessel. The incident neutral flux densities decay rapidly with distance from the strike point, so that only the near-divertor area receives a significant fluence for the time period (~5-10 s) of interest here.

The net D^0 and T^0 fluxes are the implantation driving terms which determine the changes in wall composition and hence in R_T. A model for the implantation range derived from TRIM[8] is used in WDIFFUSE to relate the mean energies from the EIRENE analysis to the implantation range for each surface element. The rate at which $R_T(t)$ increases is determined by the model for D/T trapping and release in graphite.

VI. WALL SATURATION MODEL

In this analysis the most recent JET wall model of Ehrenberg[9] (extension of PTE model[5]) has been incorporated into the WDIFFUSE code[3]. WDIFFUSE treats D and T and calculates the evolution of D_2, DT and T_2. The model describes the evolution of trapped (t) and solute (s) hydrogenic species under the interaction of D and T implanted fluxes. For the discharges discussed here, the diffusive terms are neglected, since they operate over a longer (post-discharge) time-scale[5].

In the implantation zone the model equations for the solute concentrations are

$$\frac{dc_s^D}{dt} = -k_0 (c_s^D)^2 - k_0 c_s^D c_s^T - \frac{dc^D}{dt} + \Sigma^D \qquad (1)$$

and

$$\frac{dc_s^T}{dt} = -k_0 (c_s^T)^2 - k_0 c_s^D c_s^T - \frac{dc_t^T}{dt} + \Sigma^T . \qquad (2)$$

For the trapped concentrations, the equations are

$$\frac{dc_t^D}{dt} = k_{s,t} c_s^D \left(1 - \frac{(c_t^D + c_t^T)}{c_{t,s}}\right) - k_{t,s} c_t^D - k_d c_t^D (\Sigma^D + \Sigma^T)^{1/2} \qquad (3)$$

and

$$\frac{dc_t^T}{dt} = k_{s,t} c_s^T \left(1 - \frac{(c_t^T + c_t^D)}{c_{t,s}}\right) - k_{t,s} c_t^T - k_d c_t^T (\Sigma^D + \Sigma^T)^{1/2}, \qquad (4)$$

where subscripts t and s refer to trapped or solute states, D and T refer to the atom species (deuterium or tritium), Σ is the implantation rate, c_s^D and c_s^T are the solute concentrations for D and T, k_o is the recombination coefficient, $k_{t,s}$ is the thermal detrapping coefficient, $k_{s,t}$ is the trapping coefficient, and k_d is the particle-induced detrapping coefficient. Table 1 summarizes the values for the coefficients (taken from the PTE model of Refs. 5 and 9) that were used in the WDIFFUSE code.

The initial T uptake in 41677 using these coefficients and the implantation fluxes and energies from EIRENE are shown in Fig. 5. In these calculations it is assumed that, initially, the near-surface trapping sites are fully saturated with D. The resulting values of the D and T recycling coefficients are inferred from EIRENE analysis of the difference between the divertor and sub-divertor T concentration. Also shown is a variation in the PTE reference data such that the particle-induced detrapping coefficient, k_o, is increased by a factor of 2 and decreased by 0.5. Modest variations have a significant effect on

Table 1. Coefficients used for the physical processes described by Equations 1 to 4 and included in the WDIFFUSE Code.

Recombination coefficient: k_o	10^{-21} cm^3/s
Trapping coefficient: $k_{s,t}$	10^4 s^{-1}
Thermal detrapping coefficient: $k_{t,s}$	0.0
Particle-induced detrapping coefficient: k_d	6×10^{-13} $cm^{3/2}$ $s^{-1/2}$

(1) the magnitude of the D-T exchange and (2) the rate at which the transition to the new recycling levels occurs. It is encouraging that this set of coefficients do a reasonable job of describing the T recycling coefficient. An even better agreement could be obtained by increasing k_d to ~ 3 times the PTE value or $k_d = 6 \times 10^{-13}$ $cm^{3/2}$ $s^{-1/2}$.

VII. CONCLUSIONS

These recent D-T experiments on JET have provided a unique opportunity to study the isotopic exchange processes in a large tokamak as the initially D saturated wall is filled in subsequent discharges with T. These experiments have been analyzed with a quantitative model which treats the dynamic exchange between the recycling surfaces and the edge plasma region. Experimental measurements of the sub-divertor tritium concentration, when compared with divertor tritium concentration measurements near the strike point, show significant differences during the initial tritium uptake experiments. This difference is a sensitive measure of the status of the wall T saturation. The neutral transport code EIRENE has been used to evaluate the range of wall tritium recycling coefficients (R_T) which is consistent with the observed sub-divertor and divertor strike point data. A wall hydrogenic trapping and diffusion code is then used to compare these values of R_T with expectations based on present laboratory values for fundamental wall rate coefficients. Bulk recombination, trapping in graphite, thermal detrapping, bulk diffusion, and particle-induced detrapping from ion and neutral fluxes are all included. Wall rate coefficients from the PTE model[9] were found to give good agreement with observed T recycling.

The level of T saturation for the first few atomic layers of the divertor wall is important in determining the dynamics of T recycling within a single discharge. For the discharges investigated here, it appears that T located in co-deposited layers does not contribute a significant amount to the T dynamics within a single discharge. This is expected since the T in co-deposited material appears to be located in remote areas of the divertor[6]. The dynamic inventory model, presented here, thus provides a detailed, testable hypothesis for the evaluation of edge plasma models under other conditions and looks promising for the development of a predictive plasma transport model.

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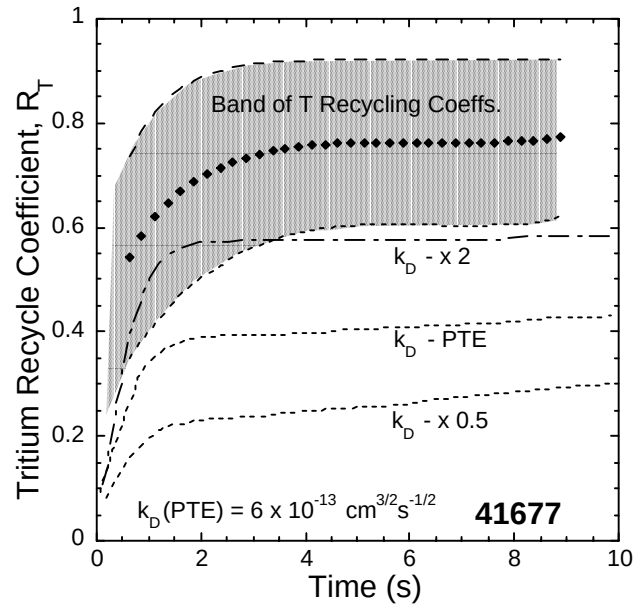

Fig. 5 WDIFFUSE calculation of T recycling coefficient during implantation of D and T into D-saturated wall.

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