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Modelling of plasma tritium concentration and wall tritium inventory at JET

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Abstract

In this paper a method for the calculation of the wall particle inventory in a Tokamak is proposed and applied for a series of discharges carried out during the recent Joint European Torus (JET) D–T experiments. These results are subsequently used to validate a new model for the calculation and prediction of the wall particle inventory on the pulse by pulse time scale. This model, known as the 'Wall Retention' model, includes the effect of codeposition and is able to reproduce both the total and the tritium wall inventory if it is assumed that between 0.8% to 2% of the ion flux to the divertor is codeposited. It is demonstrated that the Wall Retention model can be used predictively while maintaining good agreement with the experiments. Extrapolations to ITER give a tritium retention per pulse of 54 g. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Wall particle content; JET; Deuterium; Tritium; Tritium inventory; Tritium retention; Divertor; Codeposition

1. Introduction

In moving towards the development of future fusion reactors, the tritium wall retention and the associated safety issues have emerged as one of the crucial issues to be addressed. This paper reports upon the development and application of new methods [1] for the determination and prediction of the tritium inventory under reactor-like conditions.

Recently, a series of experiments have been carried out at the Joint European Torus (JET) in which tritium fuel has been used in large quantities for the first time [2] in this machine. Since the tritium content in the wall was negligible prior to these experiments, it was possible to determine the amount of tritium retained in the wall during plasma operations. These measurements have allowed one to improve and validate models for the simulation and prediction of the tritium particle inventory in the vessel wall.

In order to predict the plasma–wall interactions during a discharge and, in particular, the contribution of the wall recycling to the plasma fuelling, several wall/plasma models have been developed over the years [3–10]. These models have a high level of sophistication and require knowledge of the time dependent measurements of several plasma parameters. This method of determining the wall particle inventory is computationally expensive and precludes the analysis of a large number of discharges.

An alternative approach is adopted in the Multi-Reservoir model [11]. By introducing assumptions about the plasma–wall interactions, this model focuses upon the wall particle inventory and isotopic composition without requiring detailed information on the time dependent plasma behaviour. In this paper, a new model,

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called the Wall Retention model, is derived from the Multi-Reservoir model, by adding the contribution of codeposition to the retention of plasma particles in the wall [1]. The model is validated against a series of D–T discharges and the results are discussed. A prediction of the ITER inventory is carried out based on the results of the JET D–T experiments.

2. Experimental determination of the wall particle inventory

The global wall particle inventory is calculated from the balance

$$\Delta R_W = N_{in} - N_{CP} - N_{exh} \quad (2.1)$$

where

- ΔR_W is the net increment to the wall particle inventory after each discharge
- N_{in} is the number of particles injected per discharge
- N_{CP} is the number of particles pumped by the cryo-pump, given by

$$N_{CP} = 2 \cdot \frac{S_{CP}}{kT_D} \int_{\text{pulse}} P_D \mathrm{d}t \quad (2.2)$$

P_D and T_D being the pressure and the average temperature in the sub-divertor volume, k the Boltzmann constant and S_{CP} the cryo-pump pumping speed at the pump plenum. The factor 2 takes into account that the hydrogenic molecules are diatomic.

- N_{exh} is the number of particles exhausted from the wall by thermal outgassing between pulses, given by

$$N_{exh} = 2 \cdot \frac{S_{TP}}{kT_{torus}} \int P_{torus} \mathrm{d}t + 2 \cdot \frac{S_{CP}^{torus}}{kT_{torus}} \int (P_{torus} - P_o) \mathrm{d}t \quad (2.3)$$

P_{torus} and T_{torus} being the torus pressure and average temperature, S_{TP} the turbo-pump pumping speed, S_{CP}^{torus} the cryo-pump pumping speed in the torus, and P_o the vapour pressure at the cryo-pump.

To calculate the tritium retention in the wall, Eq. (2.1) is used, taking into account the fraction of tritium in the gas injected, in the sub-divertor volume (measured at JET by visible spectroscopy diagnostics [12,13]) and in the gas released from the vessel (measured with the JET Gas Collection System [1] and an ionisation chamber [14]).

All the parameters required for the particle balance are calibrated and the method is applied to the discharges performed during the first two weeks of the JET D–T experiments, in 1997. These discharges comprise various regimes of ohmic, L-mode and ELMy H-mode. The results are presented Fig. 1 and compared to independent calculations from the JET Active Gas Handling System (AGHS) [15] and from daily gas balance estimated after the regeneration of the divertor cryo-pump. The AGHS measurements are the most accurate, but provide data only when the gas collected from the torus vessel is reprocessed. The daily gas balance data may be affected by systematic errors due to the uncertainties in the temperature of the gas after the regeneration, in the ionisation chamber measurements for the presence of hydrocarbons, and, for low T concentration, to tritium contamination of the ionisation chamber. Despite these systematic errors that may produce an underestimate with respect to the AGHS data, the data are within 30%. The pulse by pulse measurements are normalised to the daily gas balance data, and can also be affected by systematic errors in the measurements of the pressure in the sub-divertor volume, from JET pulse number #41800. Nevertheless, the pulse by pulse measurements are valuable for the study carried out in this paper since they show the detailed evolution of the wall particle inventory.

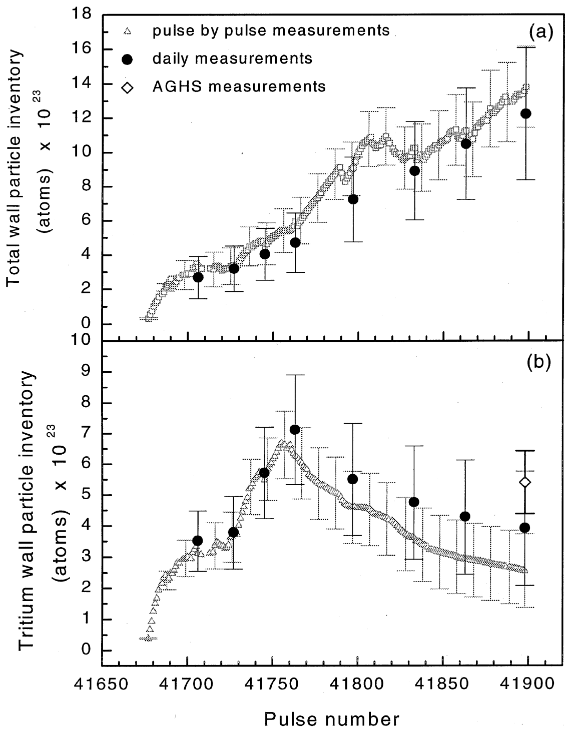

Fig. 1. Tritium (a) and total (b) wall particle inventory as a function of the JET pulse number, calculated with the method presented and compared to independent methods (Active Gas Handling System results (red squares) and daily gas balance (black circles)). The AGHS data are the freest from systematic errors. The pulse by pulse measurements could be affected by systematic errors that cause the tritium retention to be underestimated during the tritium clean-up.

3. The upgraded multi-reservoir model

The Multi-Reservoir (MR) model was originally developed to simulate the H/D fraction in the plasma and the gas released from the wall during experiments in which the isotopic composition of the plasma and the wall were changed from deuterium to hydrogen and vice versa [11]. At this time, no attempt was made to simulate the wall particle inventory. It was observed that the time decay of the initial isotope in the gas released after each plasma discharge could be described in terms of two time constants: a fast one with a characteristic time of a few plasma discharges and a long term one of tens of discharges. This behaviour was therefore modelled in terms of two wall particle reservoirs, one representing the main recycling surfaces (fast reservoir) and one representing the less accessible regions of the machine (slow reservoir). It was assumed that the fast reservoir is in isotopic equilibrium with the plasma when in contact with it, and outgasses between discharges with an outgassing rate following a power law of the type t^{-n} (with $n = 0.5$ to 1, describing a diffusion/recombination process) [16]. The slow reservoir exchanges particles with the plasma at a constant rate S_S, but does not come in contact with the plasma at any time. The MR model calculates the tritium fraction in the fast reservoir from the balance between the particles externally fuelled into the plasma, the particles contained in the plasma, the particles exchanged between the plasma and the slow reservoir, and the particles outgassed by the fast reservoir between pulses. In order to model JET plasma discharges performed after the installation of the pumped divertor, the MR is upgraded to include a term representing the effect of the cryo-pump on the overall particle balance.

The comparison between the experimental data and the model calculations have been used to identify the most suitable values of the parameters in the model to reproduce the following:

- The experimental values of the tritium fraction in the plasma and in the exhaust gas.
- The evolution of the particle wall inventory.
- The total wall outgassing for both tritium and deuterium particles.

The set of parameters that was found to satisfy better the above requirements is $n = 0.6$, $N_S = 5 \times 10^{23}$ atoms, $S_S = 5 \times 10^{-21}$ atoms s^{-1}, $K_r = 1 \times 10^{-26}$ m^6 s^{-1} $S_{CP} = 120$ m^3 s^{-1}, where n is the exponent of the outgassing law, N_S is the initial value of the wall inventory in the near surface saturated layer, S_S is the exchange rate between the slow reservoir and the plasma, K_r is the recombination rate coefficient used for the outgassing (inclusive of the outgassing surface area), and S_{CP} is the divertor cryo-pump pumping speed. The values of n and S_{CP} were determined experimentally, while the remainder of the parameters were adjusted to match the data.

The results obtained with the upgraded Multi-Reservoir model and this set of parameters are shown in Figs. 2 and 3. As one can see from Fig. 2, the agreement between the calculated and the experimental tritium fraction, both in the plasma and in the exhaust gas, is excellent. The model can reproduce the evolution and the absolute value of the tritium fraction pulse by pulse. Conversely, the tritium and deuterium wall inventories (Fig. 3) are underestimated as is the total wall particle inventory, although the model can follow the main features of their evolution from pulse to pulse.

The main deficiency of the upgraded Multi-Reservoir is that it does not reproduce the pulse by pulse accumulation of the particles in the wall, which is observed experimentally. Particles could be lost through diffusion into the bulk material. However, the characteristic time scale for diffusion to the bulk (of the order of 9000 s for a penetration of 300 Å in graphite, if a diffusion coefficient of 10^{-19} m^2 s^{-1} is assumed), is too long to be responsible for the wall retention of particles, given that the average time between discharges is 2000 s. Further-

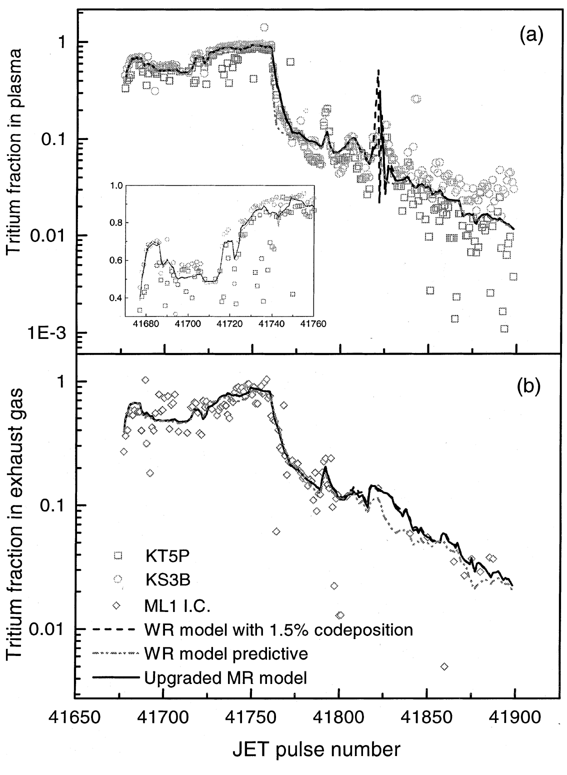

Fig. 2. Tritium fraction in the plasma (from the JET visible spectroscopy diagnostics KT5P and KS3B) (a) and in the released gas (from the JET ML1 ionisation chamber) (b) as a function of the JET pulse number. The experimental measurements are compared to the calculation with the upgraded MR model (solid line) and the WR model (dashed black and grey line).

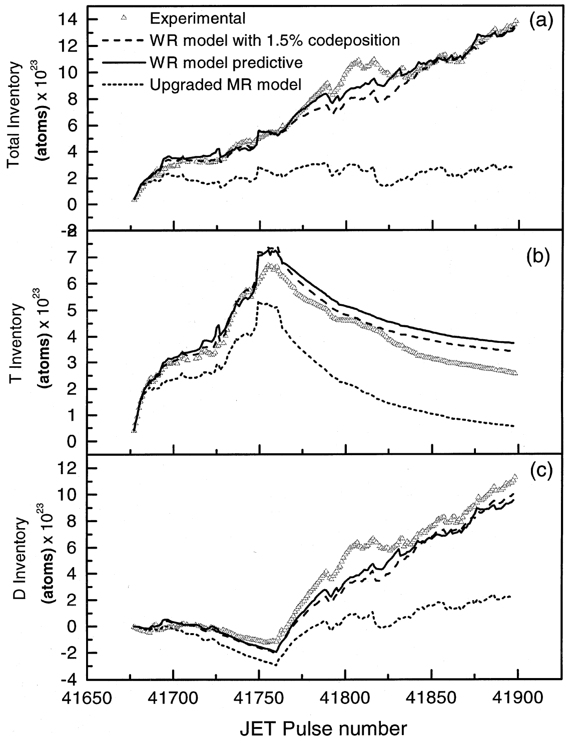

Fig. 3. Comparison between the experimental wall particle inventory (total (a), tritium (b) and deuterium (c)), the results obtained with the upgraded MR model (dotted line) and the WR model (dashed and solid line).

more, the upgraded MR model fails to reproduce the absolute value of the wall inventory for both deuterium and tritium in a similar manner even though the respective of diffusion rates are different due to their different concentration profiles into the wall material.

In conclusion, it appears that there is an isotope independent sink of particles for both tritium and deuterium atoms, which occurs discharge by discharge and should be included in the upgraded Multi-Reservoir model.

4. The wall retention model

In this paper, codeposition is proposed as the mechanism responsible for the accumulation plasma particles in the wall. Post-mortem analysis of divertor and limiter tiles, has provided experimental evidence of the retention of hydrogenic particles in codeposited layers [18–21]. More recently, following the JET deuterium–tritium campaign, flakes of wall material were observed in the divertor region, which are believed to be due to spallation of thick codeposited layers. Furthermore, Causey [22] and Wilson [23] among others, consider codeposition as one of the processes responsible for the hydrogenic retention in the vessel wall of tokamaks.

Consequently, codeposition is included in the Multi-Reservoir model which is henceforth known as the *Wall Retention model* (WR model). In the following, the approximations introduced in this work are listed and justified.

- The codeposition of hydrogenic particles only occurs at the divertor target during the X-point phase of the discharge, since in the JET Mark II divertor, the total recycling flux during the X-point phase is at least 15 times higher than in the limiter phases. Moreover, the recycling flux in the main chamber wall is at least 30 times lower than at the divertor.
- The number of hydrogenic particles codeposited during the divertor phase is proportional to the recycling H-flux at the divertor. This assumption implies that the sputtering yield is constant [24], which is reasonable at the incident energies (between 10 and 30 eV [25]), provided that the target average temperature does not change appreciably (as for the Mark II divertor tiles, with average temperatures of 600–700 K [26]), and that the neutral/ion flux ratio is almost constant. The dependence of the sputtering yield on the ion flux (between 10^{22} and 10^{23} atoms s^{-1} in the JET divertor region), has not been taken into consideration and will be investigated in future work. Moreover, most of the hydrocarbon molecules released from the wall are promptly redeposited back on the target as molecular fragments [17] (the fraction redeposited has been shown to be 95% of the released molecules [27]).
- Tritium and deuterium particles are codeposited in the same proportion as they are in the plasma. Since the codeposited plasma particles combine chemically with C atoms, the codeposition process is mass independent.

In conclusion, the number of hydrogenic particles which are codeposited during a pulse, N_{cod}, can be expressed as a fraction, F_{cod}, of the flux to the divertor during the X-point phase of the discharge, Γ_{div}, times the period spent by the plasma on the divertor Δt_{div}, as in the following equation:

$$N_{\mathrm{cod}} = F_{\mathrm{cod}}\Gamma_{\mathrm{div}}\Delta t_{\mathrm{div}}. \qquad (3.1)$$

To estimate the fraction F_{cod}, we have analysed a series of consecutive discharges having the same initial wall conditions, for which the net increment in the readily available wall inventory can be assumed to be zero. Since the wall retention is observed to be greater than zero, it is assumed that this inventory is trapped in codeposited material. From the discharges analysed, F_{cod} results to be between 0.6% and 2.5%.

The Wall Retention model is applied to simulate both the wall particle inventory and plasma isotopic composition determined experimentally for the D–T experiments shown in Fig. 1. The results are in excellent agreement with the experimental data, as shown in Figs. 2 and 3. The agreement was found by assuming a codeposition fraction F_{cod} equal to 1.5%. Taking into account the uncertainties in the pulse by pulse measurements, the codeposition factor could be $F_{cod} = 2\%$. On the other hand, the ion flux measured by the Langmuir probes represents a lower limit, and could be twice as high, bringing the codeposition factor to $F_{cod} = 0.8\%$. Assuming that carbon sputters as CH_4 [28] (chemical sputtering is dominant in this range of H-ions impact energies), the value of yield inferred from this codeposition factor is ~0.4%, which is broadly consistent with laboratory experiments [29].

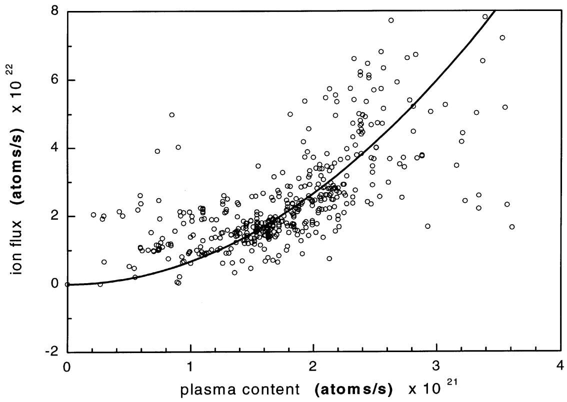

Fig. 4. The average ion flux to the divertor during ohmic or H-mode phases of the discharge is plotted against the corresponding average plasma content for all the discharges carried out during the first two weeks of the JET DTE campaign.

5. The wall retention model used predictively

Two of the input variables required by the WR model are quantities that cannot be easily estimated before the plasma discharge has been performed. These variables are the pressure in the sub-divertor volume, used to estimate the number of particles pumped by the cryo-pump divertor during the discharge, and the ion flux to the divertor, used to evaluate the amount of hydrogenic particles codeposited with carbon. In this paper the Two-Point model [17] for the divertor scrape-off layer is used to approximate the ion flux to the divertor as a function of the plasma density, for the set of DTE1 discharges analysed (attached plasmas). The proportionality between the ion flux to the divertor and the plasma density was experimentally verified over the periods of time when the plasma is in divertor configuration. During each discharge, the ion flux is averaged over the confinement regime, since and the relationship between the divertor ion flux and the plasma particle content could, in principle, change. The averaged ion flux Γ_{ion} is plotted in Fig. 4 against the corresponding averaged plasma particle content NP and fitted using a quadratic function of the type $y = a\ x^2$.

The number of particles pumped by the divertor cryo-pump during the discharge is expressed as a constant fraction of the recycling flux (measured by the ion flux), and, consequently, as a function of the plasma density. A predictive Wall Retention model is therefore derived, since the plasma density can be estimated before the discharge is carried out.

The errors deriving by expressing the ion flux to the divertor with a quadratic function of the plasma particle content, derive from the following factors:

1. The Two-Point model relates the ion flux to the plasma density at each instant in time, while the coefficient for the quadratic function have been found by interpolating time averaged values.
2. The relation between the ion flux and the plasma particle content changes if the plasma is not attached [30].

For the case of the pumped flux, additional errors are introduced because:

1. The fraction of the recycling flux that is pumped by the divertor cryo-pump depends on the position of the separatrix with respect to the pump plenum [31], although the maximum variation is $\leqslant 2$.
2. The relation between the ion flux to the divertor and the pumped flux changes dramatically if the divertor plasma is detached [25]. In particular, the neutral flux to the pump continues to follow the same behaviour, i.e. increases with the plasma density, while the ion flux drops.

The results of the WR predictive model are presented in Figs. 2 and 3. The agreement between the experimental and the calculated wall particle inventory and the tritium fraction is well within the experimental errors. It is concluded that the Wall Retention model can be used in a predictive way for attached plasmas. For the case of detached plasma the model can still be used predictively if a relationship between the particle flux to the divertor and the plasma density can be found.

6. Extrapolation to ITER

For ITER, the divertor temperature is estimated to be of the same order of magnitude as in the case of JET (approximately 700 K [32]). Assuming that the incident energy of the hydrogen isotopes on the ITER target is below 50 eV, it is reasonable to consider that the fraction of the particle flux to the divertor which is codeposited during an ITER discharge is the same as found for the JET tokamak under similar conditions, i.e. 1.5%. Taking into account that the flux to the divertor, in the detached regime, is of the order of 10^{24} atoms s^{-1} and the X-point phase for a typical ITER discharge is 1250 s, and considering a codeposition factor of 1.5%, the number of hydrogenic particles codeposited per discharge is of the order of $\sim 1.87 \times 10^{25}$ atoms equivalent to ~90 g. If the discharge is fuelled with 60% tritium, this number corresponds to ~54 g of tritium codeposited per discharge. This quantity is ~37% of the total tritium injected per discharge. Considering that the maximum inventory of tritium allowed in the vessel is ~1 kg, this implies that the machine can be operated for ~20 successive discharges (equivalent to 1 day of operation), before cleaning the vessel from the codeposited layer.

7. Conclusions

Codeposition must be introduced to model the accumulation of particles in the wall. This process is included in the new Wall Retention model for the determination of the tritium wall inventory and the fraction of tritium in the plasma. The best fit to the experimental data of the particle wall retention and of the tritium fraction in the plasma and the exhaust gas is found when it is assumed that a fraction between 0.8% and 2% of the divertor recycling flux is codeposited. The Wall Retention model can be used predictively in the case of attached plasmas. For detached plasma, the model can be used predictively if an alternative method to approximate the particle flux to the divertor is found. Moreover, since the pumping rate of the cryo-pump depends on the position of the separatrix in the divertor configuration, the Wall Retention model is sensitive to the geometry of the divertor plasma.

Extrapolating these results to ITER, it is found that ~54 g of tritium are codeposited per discharge, which is about 37% of the total tritium fuelled per pulse. This result confirms the necessity of frequent and efficient removal of codeposited layer from future fusion reactors.

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