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Role of wall implantation of charge exchange neutrals in the deuterium retention for Tore Supra long discharges

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Abstract

In Tore Supra long pulses, particle balance gives evidence that a constant fraction of the injected gas (typically 50%) is retained in the wall for the duration of the shot, showing no sign of wall saturation after more than 6 min of discharge. During the discharge, the retention rate first decreases (phase 1), then remains constant throughout the pulse (phase 2). Phase 1 could be interpreted as implantation of particles combined with a constant codeposition rate, while phase 2 could correspond to codeposition alone, once the implanted surfaces are saturated with deuterium. This paper presents a possible contribution of charge exchange neutrals to the implantation process, based on modelling results with the Eirene neutral transport code. A complex pattern of particle implantation is evidenced, with saturation time constants ranging from less than one to several hundreds seconds, compatible with the experimental behaviour during phase 1.

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1. Introduction

In next step machines, tritium retention in the carbon walls is a major concern. Tore Supra offers a unique opportunity to study this phenomenon in stationary conditions over long durations. In long pulses, particle balance gives evidence that a constant fraction of the injected gas (typically 50%) is retained in the wall for the duration of the shot, showing no sign of wall saturation after more than 6 min of discharge. This paper presents a possible contribution of charge exchange (cx) neutrals to explain this particle balance. Section 2 presents the typical particle balance for long discharges and the proposed mechanisms to explain the wall retention. Section 3 deals with the set up for modelling of the neutrals

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while Section 4 gives the results of the simulations in terms of the neutrals' spatial and energy distribution. In Section 5, consequences on the particle balance are discussed.

2. Particle balance in Tore Supra long discharges

The Tore Supra long discharge scenario, which allowed achievement of a record of pulse duration of 6 min 18 s and to couple 1.07 GJ of energy to the plasma, is described in [1]. These discharges are restricted to low current ($I_p = 0.5$ MA) and low density ($f_{GW} = 0.6$). As a consequence, the edge temperature is rather hot (in the range $T_e = 100$ eV at the last closed flux surface). Particle balance has been performed on these discharges [2], showing that a significant fraction (∼50%) of the injected flux is retained in the wall at the end of the shot. Fig. 1 shows the time evolution of the flux trapped in the wall deduced from particle balance for three consecutive long pulses. The behaviour of the retained flux is similar for the three discharges: it is first seen to decrease (phase 1, up to 100 s) and then remains constant (phase 2), showing no sign of wall saturation after more than 6 min of plasma (and ∼15 min of cumulative plasma time in three discharges, each separated by 30 min without any conditioning procedure in between). Two main processes have been invoked to explain the observed deuterium retention: direct implantation of deuterium into carbon plasma facing components and codeposition of deuterium with carbon as hydrocarbons C_xD_y, born from chemical erosion and redeposited in shadowed areas. The first process will

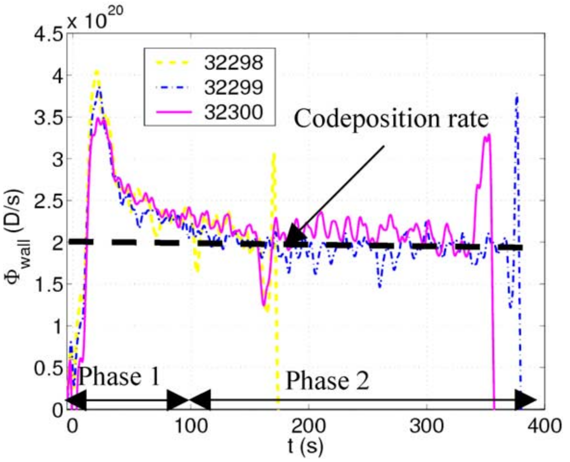

Fig. 1. Particle flux trapped in the wall calculated from particle balance for three consecutive long discharges. The two phases observed in the wall retention rate behaviour are indicated. The codeposition rate, corresponding to phase 2, is also shown (dashed line).

eventually stop when the carbon surfaces are saturated with deuterium at a given maximum concentration, while the second process will not, as redeposited layers continuously build up. Phase 1 could be interpreted as a constant codeposition rate of deuterium with carbon combined with the progressive saturation of carbon surfaces by direct particle implantation. Phase 2, with a constant wall retention rate (2×10^{20} D/s for a typical long discharge, see Fig. 1), would correspond to codeposition alone, once the implanted surfaces are saturated. In this paper, we study in more detail the direct implantation process. Using IR imaging of the limiter (TPL for toroïdal pump limiter), plasma density and temperature profiles in the scrape off layer (SOL) from Langmuir probe data, the ion flux recycling on the limiter has been roughly estimated (10^{22} D^+/s). A very simple model of implantation (see Section 5) leads to a fast saturation of the zone in direct interaction with the plasma (3.5 m^2 out of the 7 m^2 of the TPL) by the incident D^+ flux, and does not yield a retention rate compatible with experimental data. However, energetic charge exchange neutrals born from D^+ recycling on the TPL could also play a role in the particle implantation process. Simulations using the Eirene neutral transport code [3] have been carried out in order to estimate this contribution.

3. Neutral particles modelling set up

As the scope of the present work is to give a rough estimate of the neutrals contribution, simulations have been performed with a number of simplifying assumptions, listed below. A simplified Tore Supra geometry, featuring the TPL at the bottom of the machine and the first wall, has been implemented in the code (Fig. 2). Simulations are uniform in the toroidal direction. Two particle sources have been considered: the D^+ ion flux recycling on the TPL (10^{22} D^+/s), and the D_2 gas puff (2.5×10^{20} D_2/s) launched from the outer equatorial plane. It is worth noticing that the retention rate, although a significant fraction of the injected flux, is only a small fraction of the recycling flux. In the simulations, D^+ ions are launched with an energy distribution corresponding to the assumed T_i profile and intercept the TPL on which they recycle, leading to the formation of D_0 atoms and D_2 molecules, which can then in turn ionize, dissociate or charge exchange (Fig. 2). The atomic physics set up is standard (see main reactions in [4] or check the Eirene manual in [3]), only the ground states are considered (for example the vibrational state of molecules, which is not expected to play a big role in the plasma conditions considered, is not taken into account). The complex 3D D^+ deposition pattern on the TPL (see [2]) is ignored here, ions are launched with a decreasing exponential profile in the radial direction with a particle flux decay length $\lambda_\Gamma = 3$ cm.

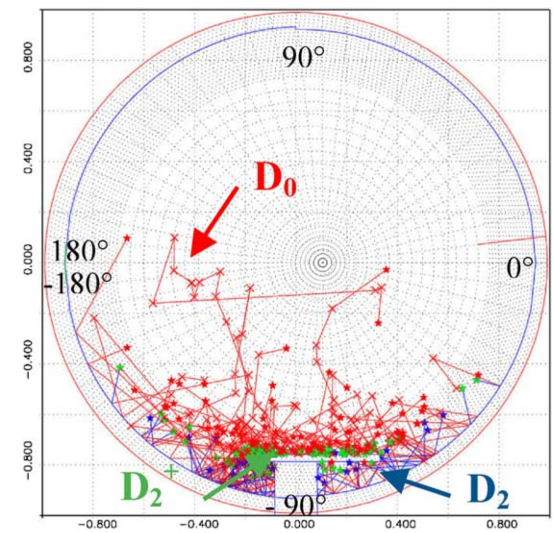

Fig. 2. Set up for Eirene modelling. The poloidal coordinate around the machine is indicated. Particle trajectories of neutrals born from D^+ recycling on the TPL are shown for illustration in the case of a recycling first wall. Along a given trajectory, crosses stand for cx reactions, stars for electron collisions (ionization, dissociation ...).

For the gas puff, thermal D_2 molecules are launched from a source point with a cosine distribution. The background plasma for long discharges conditions has been defined from experimental measurements as follows: $n_e(0) = 2.2 \times 10^{19}\ \mathrm{m}^{-3}$, $n_e(a) = 4 \times 10^{18}\ \mathrm{m}^{-3}$, $T_e(0) = 3.8$ keV, $T_e(a) = 90$ eV. The ion temperature is not measured and is deduced from power balance in the confined plasma ($T_i(0) = 2$ keV). The ion temperature in the SOL is estimated to be $2T_e$ ($T_i(a) = 200$ eV). In the simulations, reflection coefficients are calculated as for pure graphite, although a complex pattern of deposited layers has been observed in the machine [5]. The TPL is assumed to be purely reflecting (already saturated by the ion flux) and two extreme cases are considered for the first wall: purely reflecting and purely absorbing. Coupling between dedicated wall codes, such as ERO or WBC, and Eirene would be required to simulate coherently the surfaces evolution in terms of erosion/redeposition and the associated deuterium retention properties. However, the simplified set up used here allows to give a first estimate of the neutrals implantation.

4. Spatial and energy distribution of the neutrals

Results of the simulations in terms of spatial and energy distribution are summarized in Table 1. Depending on the particle source (gas puff/recycling) and the first wall recycling status (absorbing/reflecting) considered, the total number of impacting D_0, the maximum flux reached locally and the average impact energy are given for each surface (TPL and first wall). It is seen than 30% of the recycling D^+ flux impact the TPL as neutral D_0, while 20–40% (depending on the first wall recycling status) impact the first wall. Atoms are more or less uniformly distributed on the TPL, while on the first wall, they are localized around the TPL on the bottom of the machine (see Fig. 3(a)). Their distribution is uniform toroidally, and they impact on $\sim$25 m^2 of the first wall, of which $\sim$2 m^2 is made of carbon (inner bumpers). As far as the energy distribution is concerned, up to 35% of the impacting D_0 are in the 0–10 eV range, corresponding to Franck Condon atoms. The remaining particles are then influenced by cx processes and range mainly in the 10–50 eV domain, with a high energy distribution tail, yielding an average impact energy of $\sim$400 eV. This average energy is highly dependent on the T_i profile assumed in the simulations. Atoms impacting on the TPL are dominated by Franck Condom atoms (45% in the 0–10 eV range), and have a lower average impact energy (45 eV). As far as the gas puff is concerned, it is seen that a negligible fraction of the injected particles reach the TPL while 50–80% go back to the first wall as atoms (depending on the recycling status

Table 1
Results from Eirene simulations: total number of impacting particles Φ, maximum local flux Γ and average impact energy $\langle E \rangle$ of neutral atoms on the TPL and on the first wall depending on the particle source considered (D^+ recycling or D_2 gas puff) and the first wall characteristics (absorbing or reflecting)

	TPL		First wall	
	Reflecting first wall	Absorbing first wall	Reflecting first wall	Absorbing first wall
D^+ recycling (10^{22} D^+/s)	$\Phi = 2.8 \times 10^{21}$ D_0/s $\Gamma_{max} \sim 10^{21}$ $D_0\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$ $\langle E \rangle = 30$–45 eV		$\Phi = 3.9 \times 10^{21}$ D_0/s $\Gamma_{max} \sim 10^{20}$ $D_0\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$ $\langle E \rangle \sim 400$ eV	$\Phi = 1.9 \times 10^{21}$ D_0/s
D_2 gas puff (2.5×10^{20} D_2/s)	Negligible ($\sim 10^{18}$ D_0/s)	Negligible ($\sim 10^{17}$ D_0/s)	$\Phi = 4.2 \times 10^{20}$ D_0/s $\Gamma_{max} \sim 10^{20}$ $D_0\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$ $\langle E \rangle \sim 200$ eV	$\Phi = 2.5 \times 10^{20}$ D_0/s

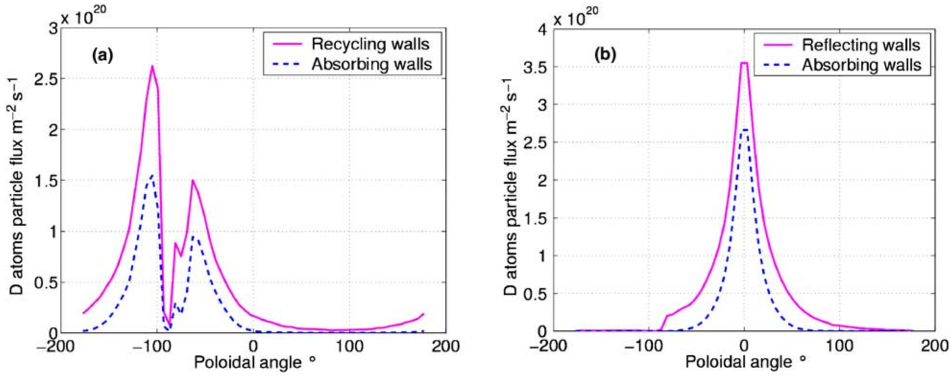

Fig. 3. Poloidal distribution on the first wall of neutrals generated by recycling on the limiter (a) or gas puff (b). In case (a), the distribution is uniform toroidally. In case (b), the distribution is peaked symmetrically around the injection point, the data shown correspond to a poloidal cut in the plane of injection. −90° corresponds to the position of the TPL, 0° corresponds to the injection point.

of the first wall). Their distribution is localized around the injection point poloidally (see Fig. 3(b)) and toroidally (results have been rescaled from the simulations assuming toroidal uniformity according to a symmetrical deposition around the injection point). They impact $\sim$2 m^2 around the injection point, out of which $\sim$0.5 m^2 is carbon when the injection is made from the outboard limiter. Their average energy is also quite high due to cx contribution, around 200 eV.

5. Consequence on particle balance

A simplistic model of particle implantation has been applied to the calculated neutral distributions: particles are implanted until a maximum D concentration in the carbon C_{Dmax} is reached ($C_{Dmax} = 10^{21}$ atom/m^2, corresponding to particles impacting with 300 eV energy [6], in the range of the average energy found above. This is also in reasonable agreement with recent measurements on Tore Supra samples [7,8]). Corrections are applied to take into account the poloidal and toroidal fraction of carbon seen by the particles. In contrast with other machines which are not actively cooled, the temperature of the plasma facing components in Tore Supra is stationary after a few seconds throughout all the discharge [1]. Therefore, there is no temperature excursions, which could play a role in particle release from the wall during a shot. The resulting retention rate is presented on Fig. 4 as a function of time for the TPL (a) and the bumpers (b), showing the progressive saturation of the surfaces up to C_{Dmax}. The implantation rate associated with D^+ is also shown: on the TPL, it is calculated from the 3D D^+ deposition pattern estimated from experimental measurements; on the bumpers, it is roughly estimated with a uniform flux in the far SOL of $10^{19}\ D^+\ m^{-2}\ s^{-1}$. The experimental retention rate attributed to implantation (obtained by subtracting the

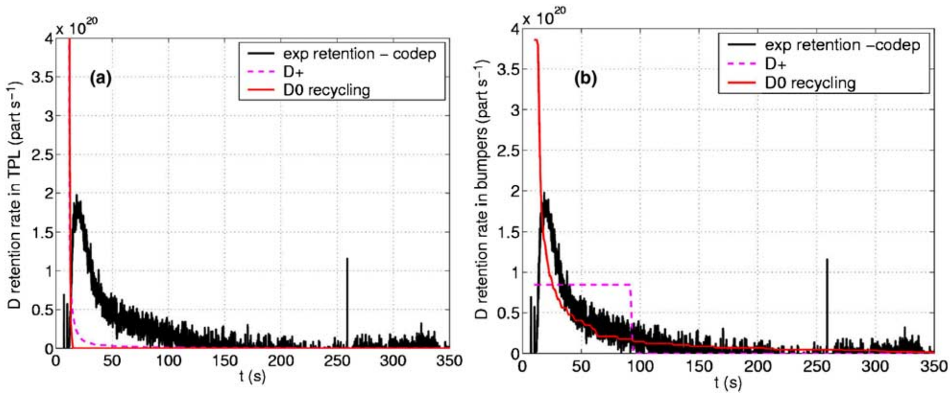

Fig. 4. Estimated retention rate from particle implantation in the TPL (a) and in the bumpers (b). Implantation of atoms coming from the recycling as estimated by Eirene calculations are presented, as well implantation from the D^+ flux. Also shown is the experimental retention rate attributed to implantation.

codeposition rate 2×10^{20} D/s to the total retention rate presented in Fig. 1) is shown for comparison. The gas puff source, not presented on the figure, leads to a very low retention rate through implantation (high flux localized on a small carbon surface). On the TPL, the D^+ and the D_0 fluxes also saturate quite rapidly the surface in direct interaction, leading to a much higher retention rate than what is experimentally observed in the first seconds, and then to a much lower flux. In contrast with other spatially peaked impinging fluxes, the D^+ fluxes on the bumpers, taken to be uniform, yield a constant retention rate until all the concerned surfaces reach saturation, which is not seen experimentally. On the other hand, implantation of the D_0 flux from recycling on the bumpers can lead to a significant retention rate over time scales compatible with the experimental behaviour. However, the above implantation model assumes to start from an empty carbon reservoir filled with deuterium during the shot, and does not explain the identical behaviour of successive discharges (Fig. 1). More refined wall models are needed to further study this issue (including diffusion in the bulk material, energy dependent implantation, trapped/solute D species in the wall [6] ...). It is worth noting that the amount of particles released between shots for long pulses is of the same order of magnitude than the trapped inventory attributed to implantation in phase 1 ($\sim 5 \times 10^{21}$, not strongly dependent on the discharge duration). This could imply a short term release process of the implanted particles, which would explain why successive identical long discharges exhibit the same retention behaviour.

6. Summary and prospects

In order to estimate the contribution of neutrals in the particle balance observed in Tore Supra long discharges, neutrals transport simulations using the Eirene code have been performed. Coupled to a very crude wall model, it allowed to evidence a complex pattern of particle implantation, with saturation time constants ranging from less than one to several hundreds seconds, compatible with the experimental behaviour during phase 1. However, refined modelling is needed to further understand the identical behaviour of successive discharges. Moreover, neutrals could also play a role in the retention process in phase 2 of the discharge, as a potential source of chemical erosion. Both issues are currently being investigated. With its ability to pursue long discharges with actively cooled components, Tore Supra offers a unique opportunity to distinguish between the different processes at stake in deuterium retention over time scales relevant to ITER discharges.

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