Simulation of the influence of the operation conditions of GDC and ICWC on isotope exchange in Be layers as mean of T inventory control in ITER

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1. Introduction

In the nuclear phase of ITER, wall conditioning will certainly contribute to the control of the tritium inventory - a major safety issue since the agreed safety limit inside the vessel must be kept under 640g during D:T operation [1] - by depleting tritium from the walls and in particular from that co-deposited with beryllium. Fuel retention experiments and post-mortem analysis in JET with ITER-like Wall (ILW) suggests that fuel implantation in Be and W dominates at first followed by fuel co-deposition with Be on top of the divertor tiles [2, 3]. In this aim, isotopic exchange is a good candidate to control tritium inventory, by replacing co-deposited or implanted tritium by deuterium in Glow Discharge Conditioning (GDC) or Ion Cyclotron Wall Conditioning (ICWC) plasmas. High efficiency has been reported, in particular on JET-ILW [1, 4, 5]. The isotopic exchange mechanisms at play in beryllium layers have been investigated by a 1D Diffusion Trapping Model for Isotopic eXchange – DITMIX [6, 7] validated against experimental profiles of hydrogen isotopes in beryllium layers deposited and irradiated in laboratory [6]. It reveals that the key factors influencing isotope exchange in such layers are flux, fluence and temperature. It is here applied to extrapolate trends on T removal efficiency vs temperature, expected flux and fluences during GDC or ICWC operation in ITER.

1. Isotope exchange experiments in JET-ILW

The efficiency of fuel removal by isotopic exchange with GDC and ICWC has been assessed in the JET-ILW [1, 4, 5]. Table 1 gives particle balances, integrated over the cumulated discharge durations in each experiment.

Table 1 : particle balance in GDC and ICWC experiments on JET

	H_2-GDC	D_2-ICWC	H_2-ICWC
RF cumulated duration	5000 sec., continuous	85 sec.	218 sec.
		5-10 sec. pulse, dwell~30 min.	
Removal (atoms)	10.10^{22} H	$2,9.\ 10^{22}$ H	$6,2.10^{22}$ D
Retention (atoms)	10.10^{22} D	$2.5.\ 10^{22}$ D	$8,9.10^{22}$ H

Particle balances evidenced an accessible reservoir for isotopic exchange, i.e. the amount of wall atoms that can be replaced by the ICWC discharge specie, up to 10^{23} atoms for GDC operated nearly one and a half hour, and 6.10^{22} for ICWC operated in multi pulse mode [8], with discharges typically lasting 5-10 sec. and dwell time of 30 min. Roughly extrapolated to ITER, between a tenth of a mole and a mole of T could be removed by GDC or ICWC for similar durations [1].

Whereas GDC can only be operated in the absence of the toroidal magnetic field, ICWC discharges are produced in its presence, making them particularly interesting for T removal between D:T plasmas in ITER [1]. Isotope exchange with ICWC and GDC have been operated in JET-ILW with walls at 473K. in ITER, the inlet temperature of the pressurized cooling loop will be is 343K during plasmas and ICWC, the First Wall and the divertor being bakeable for conditioning up to 513K and to 623K, respectively.

2. Application of DITMIX to GDC and ICWC operated in JET and ITER

DITMIX is based on transport equations of hydrogen in metals such as used in TMAP and in other codes [9, 10]. It solves a system of partial differential equations and computes a 1D time-dependent solution for concentrations of dissolved and trapped hydrogen isotopes in beryllium [6]. The model considers two hydrogen isotopes in a-Be:H layers, either as soluted (mobile) or trapped (immobile) particles. The hydrogen transport in the film is governed by diffusion, and the model accounts for implantation, trapping, thermal and kinetic detrapping, as well as “swapping” between isotopes, introduced to simulate enhanced isotopic exchange all over the depth of the Be:H:D layer [6].

Hydrogen profiles from DITMIX were found in excellent agreement with profiles measured by ^{15}N-NRA on pre-characterized 600 nm thick Be:H layers, with H/Be=0,04, which were irradiated by D ions with well-defined fluxes and energies, for different fluences and surface temperatures. The model provides a qualitative understanding of the isotope exchange mechanisms, although modelled and measured D profiles show less agreement in the bulk. DITMIX shows that the main factors determining isotopic exchange are the irradiation flux and fluence and the surface temperature [6].

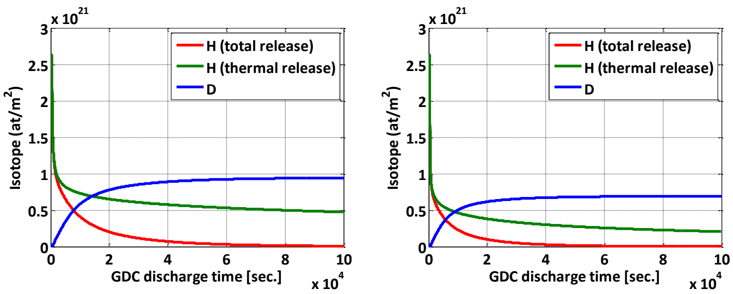

Figure 1. isotope content in the layer as a function of GDC operation time at 473K and 513K.

DITMIX was applied to GDC to simulate isotopic exchange in a 600 nm thick Be:H layer, with initial H/Be=0,04, for surface temperature of 473K and 513K. Typical D^+ ion energy of 500 eV and flux $\Gamma_D = 10^{17}$ D/m^2/s have been used for irradiation, switched on after a 500 s hold time to ensure a stable initial depth profile and switched off at t = 10^5 s. Hence, the total fluence of deuterons D = 10^{22} D/m^2.

Figure 1 shows the calculated H content in the layer as a function of time at 473 and 513K. The green curve corresponds to a pure thermal H release, while the red one corresponds to the total release of H atoms from the layer exposed to the ion flux of GDC. Although baking alone is able to remove 85–90% of the retained hydrogen, the remaining amount is removed only if GDC is applied simultaneously. After 10^5 s D_2-GDC, the Be:H layer is almost empty from hydrogen and only 0.04% of the initial H content is left in case of GDC at 513 K. Figure 2 shows the evolution of the isotope content in the layer during D_2-ICWC with $\Gamma_D = 10^{19}$ D/m^2/s, based on 0D simulations of ICWC plasma delivering an averaged flux over the entire first wall [11], and energy of 70 eV. This ion energy is probably overestimated, as ion impact energies of about 10–50 eV on the wall are expected. However the implantation depth varies very little in this energy range.

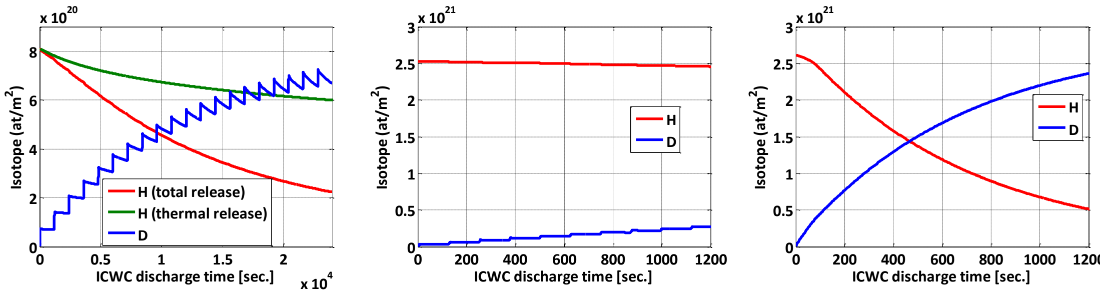

Figure 1. isotope content in the layer as a function of ICWC operation time at 473K (left), 343K in multi pulse operation (middle) and 343K in continuous operation (right).

Considering typical ICWC duty cycles in JET (Table 1), a sequence of 20 ICWC pulses was simulated at T_{surf} = 473K. In ITER, ~1200 sec. are available for conditioning between D:T pulses [1]. A sequence of 10 ICWC pulses with a duty cycle of 5/120 sec. ON/OFF has been therefore simulated and compared with continuous ICWC. Figure 2 (left) shows that at 473K, hydrogen (green and red curves) is continuously removed, while deuterium is implanted stepwise, part of it being released in the post-discharge. Decreasing T_{surf} to 343K leads to a drastic reduction of thermally activated hydrogen transport and detrapping in beryllium, thus limiting isotopic exchange efficiency. At this temperature and flux, efficiency is recovered only if ICWC is applied continuously.

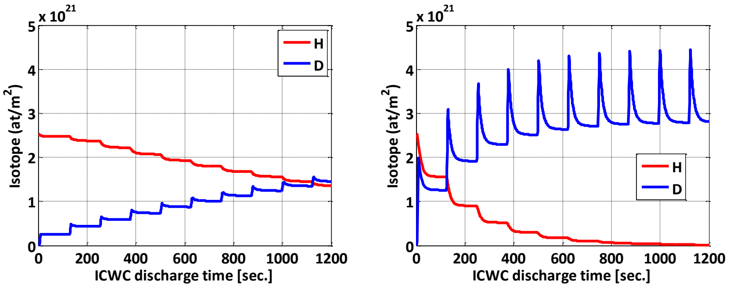

Figure 3. isotope content in the layer as a function of ICWC operation time at 343K in multi pulse operation, for $\Gamma_D = 10^{20}$ D/m^2/s (left) and 10^{21} D/m^2/s (right).

However, experimental evidence from ICWC discharges in Tore Supra [1] and in TEXTOR [12] suggest that the ion flux on limiters reaches 10^{21} D/m^2/s, this flux quickly decaying in the areas shadowed by the limiters. Fluxes of the order of 10^{20}–10^{21} D/m^2/s can be considered as an upper limit in ICWC discharges on the fully shaped ITER First Wall, without limiting surfaces. The temporal evolution of the isotope content for such fluxes is given in Figure 3. In the first case almost half of the initially retained H is removed after 10 pulses of 5 s, and a comparable amount of D is implanted in the co-deposit. For $\Gamma_D = 10^{21}$ D/m^2/s, the initial amount of H in the layers is decreased by nearly a factor 200 and the D content reaches saturation, i.e. the isotopic exchange is almost complete. It should be also noted that at this flux, erosion of Be layers by incident deuterons may not be longer negligible, leading to a possible re-deposition of the eroded material and a consequent H re-trapping.

3. Concluding remarks

Isotopic exchange with GDC or ICWC is potentially an efficient mean for the control of the tritium inventory in ITER. A 1D Diffusion Trapping Model for Isotopic eXchange –DITMIX - has been used to predict trends on the efficiency vs. expected GDC or ICWC operation parameters. The model is applied on a 600 nm thick a-Be:H layer, with H/Be=0.04, for expected wall temperatures, fluxes or fluences in ITER GDC or ICWC. Complete exchange by pulsed ICWC discharges is predicted for an ion flux to the wall $\Gamma_D = 10^{19}$ D/m^2/s impinging at E=70 eV, at T_{surf}=473K, the operation temperature in JET-ILW experiments. At T_{surf}=343K, the operation temperature of ICWC in ITER, and for the same ion flux and energy, isotope exchange is drastically reduced. Hence, one key factor determining isotopic exchange efficiency is surface temperature [6]. Complementary ICWC experiments are therefore suggested in the JET-ILW with walls at 343K, as it will be the case in ITER. For ion fluxes of 10^{20} and 10^{21} D/m^2/s, which may be considered as an upper limit in ICWC discharges on the ITER First Wall, the efficiency of pulsed ICWC is recovered at 343 K. Although complete exchange is predicted at T_{surf}=513K, $\Gamma_D = 10^{17}$ D/m^2/s and E=500 eV, representative conditions of GDC, the latter requires the absence of toroidal magnetic field, and it can therefore not be used in the silent time between ITER plasma pulses to control T inventory in ITER. In this respect GDC is not as attractive as ICWC for T-removal.

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