Ion Cyclotron discharges for Tokamak wall conditioning in presence of a magnetic field: recent experimental results on Tore Supra.

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1. Introduction

In fusion devices, the interaction of the plasma with the inner walls of the vacuum chamber releases impurities which can affect the performance of the fusion plasma. In order to control the surface state of the vacuum vessel, and thus the fluxes of impurities and fuel between the plasma and the walls, a set of techniques are used which is called wall conditioning [1]. In today's equipments, the conditioning of vacuum chambers is generally ensured by direct current glow discharges in a hydrogen or helium atmosphere. These conditioning discharges are done between plasma experiments, without magnetic field. In ITER and future fusion devices, the magnetic field will be generated by superconducting coils and thus will be continuously maintained. In the presence of such a magnetic field, the standard DC-glow discharges are unstable and can no longer be used. Depending on the choice of ITER materials (CFC or W divertor), the present estimates lead to a tritium inventory build-up to the administrative limit of 700 g T within a few hundred (CFC) or a few thousand (W) nominal full power D: T discharges [2]. In the case of a CFC divertor, the administrative limit of 700 g T would be reached within a time shorter than the allowed interval between standard glow discharges conditioning, determined by the maximum authorized number of toroidal field cycles (50 per year). Moreover, the tritium build-up could be two orders of magnitude larger in abnormal events such as disruptions [3]. In order to limit the flux of impurities from the walls, to ease plasma initiation, to control desorption of hydrogenic species and to minimize tritium inventory it is therefore important to qualify alternative conditioning techniques. The Ion Cyclotron Wall Conditioning (ICWC) technique based on RF discharges is fully compatible with the presence of the magnetic field. The ICWC technique was recently approved for integration into the ITER baseline using the ITER ICRF heating system [4]. The use of Deuterium ICWC as a possible detritiation technique was first reported in Tore Supra [5]. However, new investigations are needed prior to their validation as conditioning process and their application to ITER. Recently, Ion Cyclotron Wall Conditioning (ICWC) experiments have been carried out on Tore Supra. This paper reports on the obtained results. A description of the experimental details is firstly given. The second part reports on the assessment of the efficiency of this technique for isotopic exchange. The successful recovery after disruptions using ICWC only is reported in a third part.

2. Experimental details

Tore Supra is a large size superconducting tokamak (major radius of 2,4 m and minor radius of 0,8m) with actively cooled plasma facing components (PFCs). The PFCS are composed by 70 m^2 stainless steel alloy 316L and 14 m^2 CFC tiles of type N11, mainly located on the Toroidal Pumped Limiter (TPL). The inner walls of the torus vacuum vessel are temperature controlled at 120°C. For the ICWC experiment, the toroidal magnetic field was permanently maintained at B_T=3,8T by the superconducting coils. A He-H_2 gas mixture was used, with a hydrogen content varying from 0 to 60 %. The gas pressure in the vacuum chamber was measured with capacitance and ion gauges. Both He and H_2 throughputs were feedback controlled on the gas pressure, which was set to $p \leq 0,1$ Pa. The ICRF power was applied through a standard two straps antenna, without any change in the hardware. RF powers ranging from 30kW to 150kW were used at a RF-frequency of 48 MHz, which is within the range of ITER RF frequencies. Hence, given this field and the RF frequency, the fundamental ion cyclotron resonance frequency for hydrogen ions is located at R=2.9 m, i.e. 30 cm away from the RF antenna. The production of ICWC discharges is described in [6], [7]. The antenna was operated either in π or 0-phasing and both continuous and pulsed mode operations were performed [8]. A Neutral Particle Analyzer (NPA) was used to measure the tangential components of D and H CX neutrals produced during the ICWC discharges for energies up to 40 keV. The NPA was also providing the isotopic ratio during reference ohmic discharges burned before and after ICWC. Outgassing of hydrogen and deuterium were determined by monitoring the partial pressures of the masses of interest using absolutely calibrated quadrupole mass spectrometers (QMS) located either below the TPL or remotely. The partial pressures of He, H_2, D_2 et HD are given in Figure 1 for a typical ICWC discharge (TS#43463, P_{RF}=50 kW, p_{Torus}~0,1 Pa, He-30% H_2). As the RF power is switched ON at t=5 sec., the hydrogen particles (H atoms and H_2 ions) start to interact with wall particles, resulting in the desorption of D in the form of HD and D_2. Due to the small time for the ionisation and the re-implantation of a desorbed molecule (compared to the pumping time of a molecule in the torus), a large majority of desorbed molecules is re-deposited during ICWC. Simultaneously, a significant amount of H atoms produced in the ICWC discharge can be implanted in the walls. Once the RF power is switched off at t=65 sec., only desorption occurs in the post-discharge.

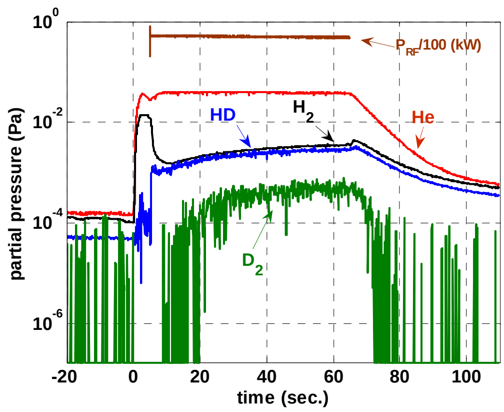

Fig.1. partial pressures of main hydrogenic species during a He-30%H_2 ICWC discharges (p=0,1 Pa, P_{RF}=50 kW)

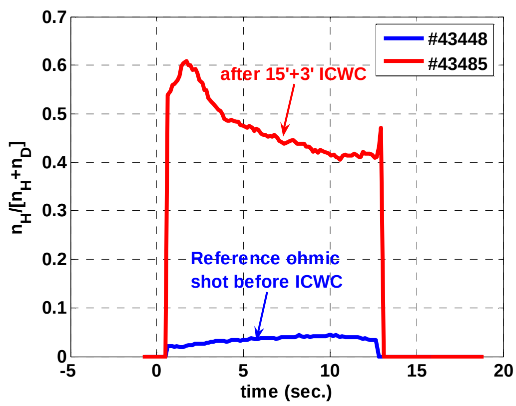

Fig.2. isotopic ratio measured by the NPA during two identical reference ohmic shots (I_p=1 MA, R=2,38 m) before and after ICWC.

3. <u>Efficiency for isotopic exchange</u>

Figure 2 shows the isotopic ratio $n_H/[n_H+n_D]$ measured by the NPA during two reference ohmic shots (D_2, I_p=1 MA, R=2,38 m) at the beginning (blue) and at the end of the experimental session (red). It can be seen that the isotopic ratio is significantly changed, from 4 to 50 %, after 850 sec. cumulated time of He-H_2 ICWC discharges.
Particle balance in each discharge was done using on one side the gas injection signals and on the other the time-integrated partial pressures of H_2, D_2 et HD, calculated from mass spectrometric data over both discharge and post discharge durations. The result is shown in

Figure 3 for the whole experimental session. It should be mentioned here, that after 850s cumulated time, the walls were saturated with H atoms implanted during ICWC. Thus, 3 min. pure He-ICWC (the 2 last shots in Figure 3) were needed in order to desaturate the walls and allow ohmic plasma initiation. Despite of that, no gas injection was needed to maintain the requested density ($N=2.10^{19}$ m^{-3}) during ohmic shot TS#43485.

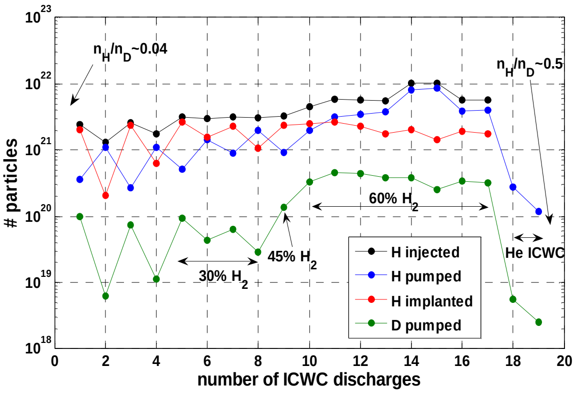

Fig.3. Result of the particle balance for each ICWC discharges. The two last points represent pure He-ICWC discharges.

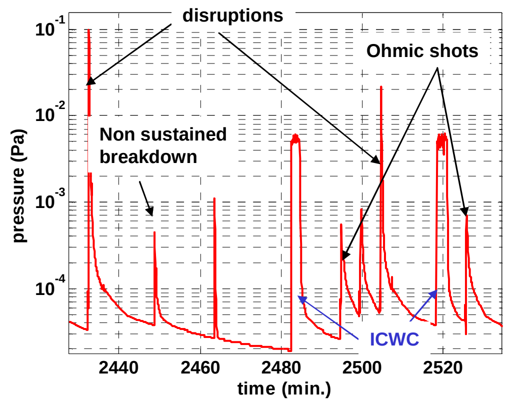

Fig.4. Total pressure in the torus measured by an ion gauge as a function of time.

Thus, during the experiments, $3,4.10^{21}$ D atoms were desorbed, essentially in the form of HD, the contribution of D_2 to the balance of D being weak. On inspection of Figure 3, it can be seen that high H_2 percentages did favor D outpumping. Simultaneously: $3,2.10^{22}$ H atoms were implanted, leading to a ratio $H_{implanted}/D_{outpumped}$ of 9.4. A progressive saturation of the walls by H atoms produced during ICWC could be seen by monitoring the H_2 depletion (i.e. the fraction of injected H_2 molecules which are pumped by the inner walls at the ignition of the RF power) which was found to decrease from 90% to 45% within 10 shots with 60 sec. duration each.

4. Recovery after disruption

In order to assess the efficiency of ICWC to recover to normal operation after an abnormal event, two disruptions were provoked on the outboard poloidal limiter during an ohmic shot at Ip=1,2 MA. The current decay rates in both disruptions were similar and equal to 360 MA/s.

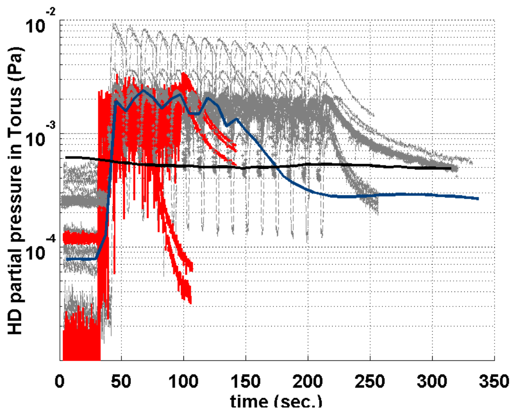

Fig.5. Comparison of HD production in different He-based conditioning techniques. ICWC: red, blue; low current ohmic pulsed discharges: grey; DC-glow discharge: black.

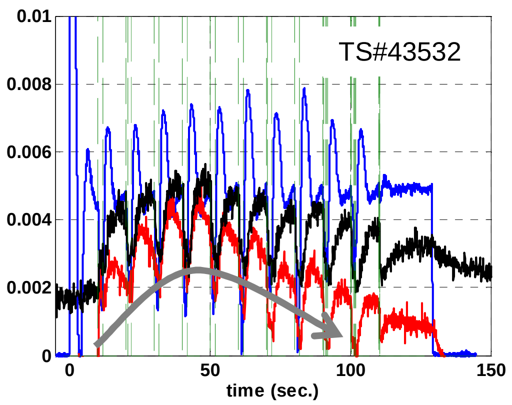

Fig.6. Mass spectrometric signals of He, H_2 and D_2O, during a pulsed He-ICWC (P_{RF}=80 kW, 2s. ON/ 8s. OFF).

The total pressure in the vacuum chamber is shown in Figure 4. Following the first disruption, the initiation of an ohmic plasma failed due to wall saturation resulting from the disruption. At t=2480 min., a pulsed He-ICWC discharge (ON/OFF = 2s/8s, 10 pulses) is used and allows successful recovery to normal operation. A second ICWC discharge, following the second disruption did allow ohmic plasma initiation.
The HD partial pressure in the Torus, measured by means of mass spectrometry during different types of conditioning discharge in Helium, is plotted as a function of time in Figure 5. As it can be seen, the levels measured in ICWC discharges are comparable with those obtained in low current ohmic pulsed discharges [9] following disruptions. The removal rate of HD molecules was found typically to be Q_{HD} ~ 1-2.10^{18} mol/s. For comparison, the HD partial pressure measured during a DC He-glow discharge right after the last ohmic shot is shown in Figure 5. The mass spectrometric signals of He, H_2 and D_2O in a pulsed He-ICWC discharge are shown in Figure 6. Since the differential pumping system of the mass spectrometer was disturbed by the preceding disruption, the data are shown in arbitrary units.
It can be seen that the signals of desorbed H_2 and D_2O are first increasing, due to the summation of the after-shot pressure levels. As the wall desaturates, the partial pressure of the desorbed species decreases. Thus, increasing the duration between two RF pulses (i.e. decreasing the duty cycle) is thought to maximize outpumping.

5. Conclusion.

ICWC is a conditioning technique compatible with the presence of a permanent magnetic field, which will be the case during ITER operation. Recently, experiments have been carried out on Tore Supra in order to assess the efficiency of this technique, in particular for fuel removal, isotopic ratio control and recovery after disruptions. The ICRF discharges were operated in He/H_2 mixtures at the Tore Supra nominal field (B_T=3.8T) and at a RF-frequency of 48 MHz. The outgassing of hydrogen and deuterium, as well as the implantation of H into the walls were measured by means of mass spectrometry. After 850 sec. He-H_2 ICWC, a significant change on the wall isotopic ratio, measured during reference ohmic discharges, could be obtained, at the price of an important implantation of H atoms into the walls. Two out of two attempts to recover from disruptions using pure He-ICWC only were successful, whereas plasma initiation would not have been possible without conditioning. It is suggested that the outpumping of desorbed species can be optimized by decreasing the duty cycle of the pulsed ICWC discharge.

References

[1] Winter J., Plasma Phys. Control. Fusion **38** (1996) 1503–1542.
[2] J. Roth, J. et al. Plasma Phys. Control. Fusion **50** (2008) 103001.
[3] Shimada M. et al. Wall Conditioning in ITER, Meeting on IC Wall Conditioning, 2 July 2008.
[4] A0 GDRD 3 01-07-19 R1.0, Design Requirements and Guidelines Level 2 (DRG2), ITER (2001).
[5] E. de la Cal and E. Gauthier, Plasma Phys. Control. Fusion **39** (1997) 1083–1099
[6] A. Lyssoivan, et al., Final Report on ITER Design Task D350.2. Brussels, 1998, LPP-ERM/KMS Laboratory Report N114 (1998).
[7] A. Lyssoivan, et al., Problems of Atomic Science and Technology **1** (13) (2007) 30-34.
[8] T. Wauters, et al., Proceedings of the 18th Topical Conference on Radio Frequency Power in Plasmas, Gent, Belgium (2009), to be published.
[9] Grisolia C. et al., Vacuum **60** (2001) 147-152