Overview of the International Research on Ion Cyclotron Wall Conditioning

D. Douai[1], T. Wauters[2] A. Lyssoivan[2], V. Philipps[3], V. Rohde[4], S.H. Hong[5], N. Ashikawa[6], V. Bobkov[4], S. Brémond[1], S. Brezinsek[3], M. Graham[7], E. Joffrin[1], G. Lombard[1], S. H. Kim[5], A. Kreter[3], D. Kogut[1], M.-L. Mayoral[7], J.-M. Noterdaeme[4,8], J. Ongena[2], B. Pégourié[1], R.A. Pitts[9], G. Sergienko[3], M. Shimada[9], S. J. Wang[5], the TORE SUPRA Team, the TEXTOR Team, the ASDEX Upgrade Team, the KSTAR team, JET EFDA Contributors* and the ITPA Topical Group on Scrape-Off-Layer & Divertor

[1]CEA, IRFM, F-13108 St-Paul-Lez-Durance, France

[2]LPP-ERM/KMS, Association Euratom-Belgian State, 1000 Brussels, Belgium, TEC partner

[3]IEK-Plasmaphysik, Forschungszentrum Jülich, Euratom Association, 52425 Jülich, Germany, TEC partner

[4]Max-Planck Institut für Plasmaphysik, Euratom Association, 85748 Garching, Germany

[5]National Fusion Research Institute, 113 Gwahangno, Yusung-Gu, Daejeon, 305-333, Korea

[6]National Institute for Fusion Science, Toki 509-5292, Japan

[7]CCFE, Culham Science Centre, OX14 3DB, Abingdon, UK

[8]Gent University, EESA Department, B-9000 Gent, Belgium

[9]ITER Organization, Route de Vinon sur Verdon, 13115 St. Paul lez Durance, France

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E-mail contact of main author: david.douai@cea.fr

Abstract. This paper gives an overview of the experimental and modeling activity on Ion Cyclotron Wall Conditioning (ICWC), with hydrogen as working gas, in order to assess the applicability of this technique on ITER for recovery from disruptions, vent or air leak, recycling control and mitigation of the tritium inventory build-up. Experimental results obtained on TORE SUPRA, TEXTOR, ASDEX-Upgrade, JET, KSTAR and LHD are presented. The conditions for safely producing RF plasmas with conventional ICRH antennas have been carefully investigated. Discharge homogeneity has been improved by adding a small poloidal component to the toroidal field. Proper choice of the duty cycle RF on/off allows mitigating re-implantation of wall desorbed particles reionized in the ICWC discharge. A 0-D model of ICWC plasmas in He and H_2 has been developed which reproduces experimentally determined electron density, neutral and ion fluxes. The installation in 2010/11 of the ITER like wall (ILW) in JET, allows now assessing the efficiency of ICWC for fuel removal on the ITER material mix. Experimental observations in carbon devices and modeling seem to indicate that ICWC, like other plasma-based conditioning techniques, interacts preferentially with transient reservoirs rather than in co-deposited layers. An attempt is made to extrapolate the found fuel removal rates to ITER.

1. Introduction

Wall conditioning techniques compatible with high permanent magnetic fields are mandatory in ITER and future superconducting fusion devices, since conventional DC-glow discharges can no longer be used in that case. However, interpulse and overnight wall conditioning will be required for reliable discharge initiation, recovery from disruptions, recycling control and may also contribute to the control of the tritium inventory in ITER by isotope exchange [1]. Encouraging results with Ion Cyclotron Wall Conditioning (ICWC), have been obtained over the past years on current Tokamaks using conventional Ion Cyclotron Resonance Frequency (ICRF) heating antennas. ICWC has now been integrated into the ITER baseline as a functional requirement of the ICRF heating system [2] for the conditioning of the first wall.

This paper gives an overview of the experimental and modeling activity coordinated by the International Tokamak Physics Activity (ITPA) Topical Group on Scrape-Off-Layer & Divertor, in order to consolidate this technique and to assess its applicability to ITER. The first part of this paper deals with specifications of ICWC for its application to ITER and the operational domain for the simulation of ICWC scenario at ITER full and half field in TORE SUPRA, TEXTOR, ASDEX-Upgrade, JET, and KSTAR. The conditions for safely producing RF plasmas with conventional ICRH antennas are discussed in this part. Optimization of ICWC discharges are discussed in a second part, as well as ICWC discharge modeling. Efficiency of D_2 or H_2-ICWC for fuel removal, assessed on different PFCs (especially on JET-ILW), as well as its ability to access co-deposited layers in the divertor and/or in gaps of castellated structures, where most of the T-retention is expected to occur, are discussed. An extrapolation of the efficiency of ICWC to the ITER case is finally attempted.

2. Specifications of ICWC for its application to ITER and operational domain in current tokamaks

2.1. Specifications of ICWC and operational parameters

In ITER, ICWC is foreseen for interpulse and overnight wall conditioning. This implies that the toroidal field is either fixed at 2.65T (He:H phase) or 5.3 T (D:T phase). With RF frequencies of the ICRH generators ranging from 40 to 55 MHz, and thus f/B_T values of 7.5 – 10.5 MHz/T, Ion Cyclotron Resonance (ICR) layers for D^+ ions at $B_T = 5.3$ T lie on ITER's magnetic axis at $\rho = 0$, i.e. above the divertor, and at $\rho = -0.6$, respectively, with $\rho = r/a$ the normalized radius ($-1 \leq \rho \leq 1$). At B_T=2.65 T, ICR layers for the protons lie at the same positions at the same frequencies. Deuterium-ICWC operation in an equivalent ITER full-field scenario can only be simulated in the largest present-day tokamak JET, with ITER-relevant f/B_T value of 7.5 MHz/T [3], at $B_T = 3.3$ T and f = 25 MHz, with on-axis $\omega = \omega_{CD}+$. Similarly, ITER half-field ICWC scenarios have been simulated in ASDEX Upgrade (AUG), as well as in TORE SUPRA, TEXTOR and KSTAR at f/B_T ~15 MHz/T with on-axis ICR layers for the protons.

2.2. Conditions for safely producing RF plasmas

Mechanisms of ICRF plasma production for conditioning are well described in [4], [5]. ICWC discharges are low density (between 10^{16} and 10^{18} m^{-3}) and low temperature ($1 < T_e < 10$ eV) plasmas [3]. Special attention is paid here to the initial breakdown phase, considered as the most critical one and for which ICWC operational parameters have to be carefully chosen in order to avoid deleterious effects in the antenna box, such as arcing. The oscillating RF electric field $E_{//}$ along the magnetic field lines is responsible for gas breakdown. Different plasma formation zones are distinguished, from the antenna box, where $E_{//}$ is maximum, towards a more high-field side region where electron energy becomes smaller than the ionisation threshold. In between, electrons are either trapped in the electric field in front of the antenna or expelled by effect of the Lorentz force, gaining sufficient energy to initiate ionization either in front of the antenna or anywhere else in a toroidal belt inside the torus. The radial decay length of $E_{//}$, which depends on the antenna toroidal size and on the current phasing between the antenna straps, is maximum for monopole phasing, which improves both the breakdown time and the coupling efficiency. The higher the operation frequency, the higher the amplitude of the $E_{//}$ needed to ionize the gas and the higher the voltage to be applied to the antenna straps. For a safe initiation of ICWC discharges however, RF voltages/power and RF frequency have to be reduced to technically available minimal values which allows RF breakdown, while avoiding spurious plasma formation in the antenna box. As pointed out in [5], the analytical description of electron motion in the oscillating $E_{//}$ field does not describe the observed pressure dependence of plasma production nor of parasitic breakdown in the antenna box [3]. It has been recently proposed in [5] that breakdown conditions in the antenna box are close those of DC breakdown at pd ≈ 0,5 Pa.cm. Next step modeling efforts describing pressure, frequency, voltage dependences of the initial plasma formation stage are currently ongoing.

3. Optimization and modelling and ICWC plasmas

3.1. Optimization of ICWC discharges

Radial and poloidal inhomogeneities can be corrected by the addition of small radial and/or vertical magnetic fields, as experimentally confirmed on TEXTOR, KSTAR and JET. Hence superimposing an additional vertical magnetic field on the toroidal field ($B_V << B_T$) allowed tilting the field lines, elongating the ICWC discharge in vertical direction to top and bottom and extending the discharge to the divertor area [3]. Similarly, improved radial uniformity of the discharge towards the high field side (HFS) could be achieved by application of $B_R << B_T$. On JET, the homogenization of the ICWC discharge was confirmed by the line integrated density profiles measured on bottom horizontal and vertical cords at the high field side of the interferometer and by the total pressure, measured higher during the discharge and the post-discharge in the presence of the poloidal field, indicating that the ICWC discharge interacts with larger area [3].

Progressive wall saturation by H_2 or D_2-ICWC has been observed, and in particular on the superconducting tokamaks TORE SUPRA [7] and KSTAR [6], where discharges could be operated continuously over long durations. In ICWC plasmas, with density between 10^{17} and 10^{18} m^{-3}, i.e. typically 4 orders of magnitude larger than in glow discharges, the residence time of wall desorbed particles $\tau \sim \tau_i = [n_e(k_{ion} + k_{diss})]^{-1}$, where k_{ion} and k_{diss} are the ionization and dissociation rates, respectively, is much shorter than its characteristic pumping time τ_S [3].

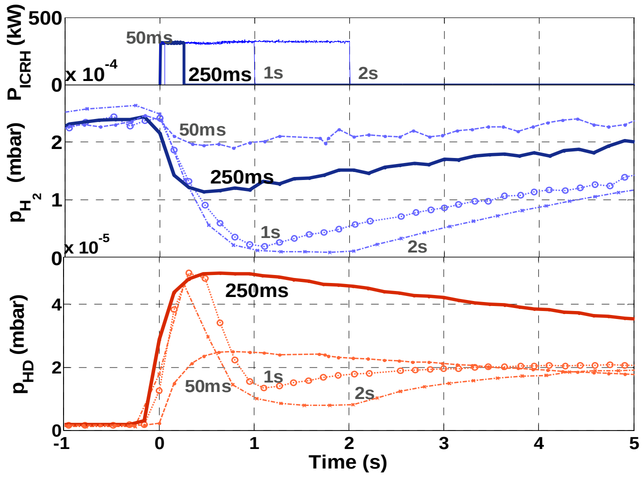

FIG. 1:H_2 and HD partial pressure in AUG H_2-ICWC discharges with different pulse durations (P_{RF}=300 kW)

The out pumped flux can be written as a function of the wall desorbed flux: $Q_{outpumped} = (1 - f) Q_{desorbed}$, the probability $f = \tau_i^{-1}/(\tau_S^{-1} + \tau_i^{-1})$ that a wall desorbed particle is ionized or dissociated and subsequently lost the walls before being pumped out, being close to 1. Reionization of desorbed species, and finally particle retention, are only present when the RF power is on and can therefore be mitigated by pulsing the ICWC plasma. The influence of the pulse duration on the outpumping on TORE SUPRA and TEXTOR in H_2-ICWC discharges clearly evidenced the possibility to reduce the ratio of retention over exhaust towards unity for sufficiently short pulse durations vs. post-discharge time (typically 1 sec./30 sec. resp.). FIG. 2 shows the measured H_2 and HD partial pressure during four ASDEX- Upgrade H_2-ICWC pulses of varying duration. Both hydrogen wall pumping and deuterium release by the all-tungsten wall increase first with the pulse length. Above an optimal duration (250 ms under these conditions), the deuterium release is reduced by reionization and re-implantation, whereas hydrogen wall pumping is still present. Pulsed He-ICWC discharges have been successfully applied on TORE SUPRA to recover normal operation after disruptions, when subsequent plasma initiation would not have been possible without conditioning [3].

3.2. ICWC discharge modeling

On current tokamaks, most of the diagnostics used are not adapted to the low density and low temperature ICWC plasmas. A kinetic model, solving the energy and particle balance equations in 0-D, has been developed in order to obtain insight on ICRF plasma parameters, particle fluxes to the walls and the main collisional processes [8].

Based on an existing code developed in [4], the present model has been extended to hydrogen molecules and helium species. It includes elastic and inelastic collision processes such as excitation, ionization, dissociation, recombination, charge exchange, as well as Coulomb and ion-neutral elastic collisions for the following 9 species: H, H^+, H_2, H_2^+ , H_3^+ , He, He^+, He^{2+} and e^-, as well as energy confinement losses and RF power coupled to charged species. Calculated values of the density, neutral and ion fluxes are in very good agreement with those determined experimentally on TORE SUPRA [9], and TEXTOR (FIG. 2 left): 10^{18}–10^{20} $m^{-2}.s^{-1}$ for H-atoms, and 10^{16}–10^{17} $m^{-2}.s^{-1}$ for H^+-ions. The model confirms that neutral hydrogen atoms constitute the dominating particle wall flux, besides ions, even in He-ICWC [8], [10], evidencing that wall surfaces are acting as major particle sources. In carbon devices, the chemically active H neutrals may be responsible for the erosion of co-deposited layers.

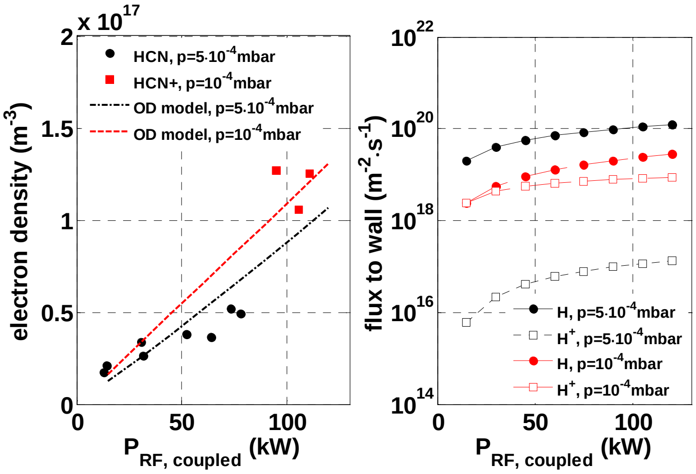

FIG. 2. calculated and measured densities (left) and wall fluxes (right) as a function of coupled power in a TEXTOR H_2-ICWC discharge ($P(H_2) = 10^{-2}$ Pa and 5. 10^{-2} Pa, $B_T = 2.3T$ and $B_V = 0.04T$).

4. Efficiency of ICWC for fuel removal

4.1. Assessment of fuel removal efficiency on current tokamaks

Significant isotopic exchange with H_2 or D_2-ICWC discharge on TORE SUPRA (CFC), ASDEX Upgrade (all-W), TEXTOR (graphite), and JET (CFC) has already been reported in [3], [11]. In all devices, the efficiency of ICWC was assessed by measuring partial pressures, either using absolutely calibrated quadrupole mass spectrometers (QMS) or optical penning gauges (JET). In that case, particle balances were calculated including active phases (RF on) and a few characteristic pumping times τ_S (no plasma). In JET, the exhausted gas was also collected by the active gas handling system (AGHS), quantified and analyzed for its components by gas chromatography [12]. On carbon machines, H_2 or D_2-ICWC discharges operation leads to retention always higher than exhaust (except for short pulse durations [3], [11]), as well as on the all-W ASDEX Upgrade, where removal efficiencies comparable to those measured on JET-CFC were recently obtained by operation of two antennas in monopole phasing. Hence, within 14 H_2-ICWC discharges on ASDEX Upgrade with cumulated discharge time of 51s, $7{,}3.10^{21}$ D particles were exhausted for a retention about five times higher ($3{,}5.10^{22}$ H).

The installation in 2010/11 of the ITER-Like Wall (ILW) in JET, has allowed a recent assessment of the efficiency of ICWC for fuel removal on the ITER material mix. Scenarios simulating ITER full-field D_2-ICWC identical to those used on JET-CFC were operated, thus allowing a comparison of the efficiency on carbon and Be/W. The noticeable difference was the absence of cryo-pumping, for technical reasons, during the experiment on the JET-ILW. Gas injection had therefore to be adjusted to optimize the isotopic exchange efficiency of D_2-ICWC discharges. FIG. 3 shows the isotopic ratio H/(H+D) as a function of the ICWC cumulated discharge time measured by means of mass spectrometry in the divertor pumping ducts during post D_2-ICWC discharges on JET CFC and ILW. In both cases, the walls were preloaded with H_2-GDC beforehand (2 and 4 hours on JET-CFC and JET-ILW resp.). On Be/W, the high isotopic ratio H/(H+D) drops from 40% to 5 % within first 60 s of cumulated D_2-ICWC discharge time, remaining approximately constant in the subsequent ICWC pulses, indicating that surfaces can not be depleted of H atoms after this time. The isotopic ratio is measured higher with carbon PFCs, with a somewhat slower variation (from 70% to 60%). However, the absence of cryo-pumping during the ILW experiment does not allow concluding on the effect of the PFC material on the efficiency. Whereas D atoms are trapped on cryo-panels in CFC experiments, their residence time in the divertor ducts was much higher during the tests on ILW, explaining lower measured values of H/(H+D). On the other hand, gas balance results, obtained from gas chromatography of the gas collected by the JET AGHS, and summarized in Table 1, show that comparable amounts of H atoms were removed by D_2-ICWC discharges in both cases, and

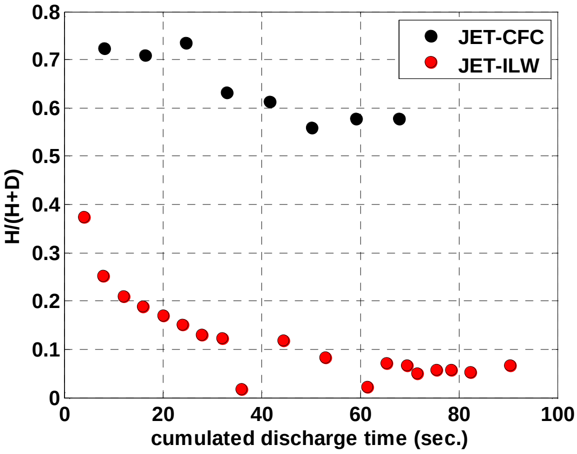

FIG. 3. Isotopic ratio as measured by mean of mass spectrometry in the divertor as a function of the cumulated ICWC discharge time in JET-ILW and JET-CFC.

this despite the observed reduction by one order of magnitude of the overall D retention after the plasma-facing material change on JET [12]. If the value is about 10% of short-term retention reported in [13] for CFC, it is of the same order than dynamic retention at the end of JET-ILW limiter discharges [14]. Whereas extra wall retention was observed on carbon (D retention was about 3 times higher than H removal), the latter was absent on the ILW, where a one-to-one isotopic exchange could be obtained. This in agreement with observations in isotopic exchange experiments with GDC on the ILW [15].

TABLE 1: Particle balance after JET-CFC and JET-ILW D_2-ICWC

	2009 - CFC	**2012 – ILW**
Duration	70 sec.	85 sec.
Recovered H-atoms	$1,6.10^{22}$	$2,9.\ 10^{22}$
D retention (atoms)	$4,8.\ 10^{22}$	$2.5.\ 10^{22}$

4.2. Ability to access co-deposited layers

The efficiency of ICWC is usually assessed from gas balance, making it difficult to state on the ability of the discharge to access co-deposited layers in the divertor and/or in gaps of castellated structures, where most of the T-retention is expected to occur. On TEXTOR, pre-characterized a-C:D layers on silicon wafers, were placed parallel or perpendicular to the magnetic field lines on a sample holder mounted into the bottom limiter lock. They were then exposed to 490 pulses H_2-ICWC discharges (duty cycle: 0,5 sec. on, 20 sec. off) at a steady-state toroidal magnetic field of 0,4T, and erosion/re-deposition was measured by means of ex-situ ellipsometry [16]. Higher erosion rates (0,4 $nm.min^{-1}$) were measured at surfaces perpendicular to the magnetic field lines, than at those parallel to it (0,25 $nm.min^{-1}$), which of the same order than those of continuous H_2-GDC on TEXTOR [16]. In LHD, thin stainless steel samples were placed on a moveable holder either facing the ICWC plasma or perpendicular to it, in a narrow gap mimicking castellations. They were then exposed to He-ICWC discharges only with a cumulated duration of 4000 seconds throughout the experimental campaign. Formation of Helium bubbles, measured by Transmission Electron Microscope, and attributed to bombardment by charge exchange neutrals measured by Natural Diamond Detector, was observed only on the side facing directly the plasma, indicating that shadowed surfaces not directly exposed to plasma were not accessed by He-ICWC [17].

A plasma wall interaction model has been developed [10] which describes macroscopically the interaction of H_2, HD and D_2 species present in a H_2-ICWC discharge calculated with the 0-D model with typical transient and permanent wall reservoirs on TORE SUPRA [9], [10]. It includes diffusion, trapping, particle induced and spontaneous detrapping and formation of co-deposited layers. These layers, resulting from the carbon erosion and its transport in remote areas of the vacuum chamber as well as deep pores of the CFC, constitute an infinite and permanent reservoir, in which atoms remain definitely retained, as it has been observed experimentally on TORE SUPRA [10]. The transient reservoir consists of particles that can be exchanged between the conditioning discharge and the carbon based walls. This accessible reservoir contains a limited number of particles, as observed from the saturation of outgassing after long discharges on TORE SUPRA [10]. The model is able to reproduce the experimental partial pressure signals in a TORE SUPRA H_2-ICWC discharge, measured by means of mass spectrometry, as shows in [9]. The model tends to indicate that H is permanently stored in the permanent reservoir (no removal from co-deposited layers is included in the model) without accessing the trapped deuterium there. However, this model is not applicable to the ITER case, where lower fuel content in co-deposited layers is expected than for carbon [12].

4.3. Extrapolation to fuel removal in ITER

The estimated T-retention lies between 0,14 and 0,5 gT per 400 s long ITER D:T shots [1]. Moreover, about 20 minutes should be available for inter-pulse ICWC between two D:T fusion plasmas pulses [18]. Table 2 summarizes the measured efficiencies for H_2 (or D_2) ICWC for fuel removal by isotopic exchange. Amounts removed are given in monolayers of D (resp. H) atoms, one monolayer containing 2.10^{19} m^{-2} atoms of the wall surfaces. Values from TORE SUPRA, TEXTOR, ASDEX-Upgrade and also JET-CFC were obtained from shot-based measurement of partial pressures, including each time a few characteristic pumping times. In particular, particle balance calculations from gas chromatography and from mass spectrometry were found in agreement on JET-CFC [3], [11].

TABLE 2: Assessed efficiencies of ICWC on current tokamaks

Tokamak	PFC	Cumul. RF time	Pulse length	Removed amount
JET-CFC	CFC	72s	9s	5 monolayers
JET-ILW	Be/W	90s	4-8s	10 monolayers
TORE SUPRA	Carbon	18 min.	~ 1 min.	2.5 monolayers
TEXTOR	Carbon	3 min.	6 – 8s	9 monolayers
ASDEX Upgrade	W	50s	0.05 – 10s	12 monolayers

Hence fuel removal efficiency in ITER can be extrapolated considering the given ICWC discharge durations and subsequent pumping times in each machine. For instance, considering a ~3 sec. discharge on AUG followed by a pumping time of 3 τ_S, one can estimate that 40 mgT are removed on ITER using an “AUG-like” conditioning cycle (RF on/RF off). Given the characteristic pumping time in ITER ($\tau_{S,ITER} \approx 40$ sec.), about ten 3 sec. long ICWC discharges, each followed by 120 sec. post-discharge could be performed and remove 0,4 gT between plasma shots. Due to the absence of cryo-pumping, characteristic pumping times during experiments on JET-ILW were much longer than on JET-CFC. Direct extrapolation from JET-ILW is therefore difficult since the total amount of atoms removed was integrated over the whole experimental session of a few hours duration, whereas the cumulated ICWC discharge duration was only 90 sec. The assessment of ICWC on JET-ILW should be therefore completed with further experiments using JET cryo-pumps. Finally, one should reasonably expect that the fuel removal efficiency will decrease with the ICWC operation time, as known in GDC. This can be seen on the rapid decrease of the wall isotopic ratio with the operation time shown in FIG. 3. Therefore, all the quantities given above allow only extrapolating upper limits of fuel removal rates to ITER.

5. Conclusion

Research on Ion Cyclotron Wall Conditioning (ICWC) is the object of effort coordinated by ITPA Scrape-Off-Layer & Divertor Topical Group to consolidate this technique for fuel removal for recovery from disruptions, vent or air leak, recycling control and mitigation of the tritium inventory build-up in ITER. Progress has been made on obtaining a clearer picture of the conditions for safely using conventional ICRH antennas. Still, the observed dependence on pressure of parasitic plasmas initiation in the antenna box has to be better understood and is currently investigated. ICWC scenarios for ITER half and full field operation are now simulated and optimized on TORE SUPRA, KSTAR, JET, TEXTOR and ASDEX Upgrade. Besides comprehensive information on ICWC discharges, 0-D modeling confirms that neutral

H atoms are the dominating particle wall flux. The high retention fraction of the wall desorbed flux in ICWC discharges can be mitigated using an appropriated duty cycle. The latter depends ion the discharges parameters (pressure, RF power) and on the type of PFCs. Hence, results from JET-ILW show that Beryllium seems to limit retention in ICWC discharges, favoring outgassing in the post-discharge, as reported in [14]. Experimental results from TEXTOR and LHD, as well as modeling, illustrate that the interaction of ICWC plasmas with carbon co-deposited layers, where most of the fuel retention is expected to occur, is less strong than the interaction with typical transient fuel-particle reservoirs. The model, based on empirical description of hydrogen plasma wall interaction in carbon machines, is however not applicable to the ITER material mix, where fuel content in Be co-deposited layers is expected lower. Extrapolation of the removal efficiencies to ITER yields encouraging results, T-removal rates by ICWC being of the same order than those of the expected retention.

Acknowledgments

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