Recent Results on ICRF Assisted Wall Conditioning in Mid and Large Size Tokamaks

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Abstract. This paper reports on the recent assessment of the Ion Cyclotron Wall Conditioning (ICWC) technique for isotopic ratio control, fuel removal and recovery after disruptions, which has been performed on TORE SUPRA, TEXTOR, ASDEX Upgrade and JET. ICWC discharges were produced using the standard ICRF heating antennas of each device, at different frequencies and toroidal fields, either in continuous or pulsed mode. Intrinsic ICWC discharge inhomogeneities could be partly compensated by applying a small vertical magnetic field, resulting in the vertical extension of the discharge in JET and TEXTOR. The conditioning efficiency was assessed from the flux of desorbed and retained species, measured by means of mass spectrometry. In Helium ICWC discharges, fuel removal rates between 10^{16} D.m^{-2}.s^{-1} to 3.10^{17} D.m^{-2}.s^{-1} were measured, with a linear dependence on the coupled RF power and on the He^{+} density. ICWC scenarios have been developed in D or H plasmas for isotopic exchange. The H (or D) outgassing was found to increase with the D (resp. H) partial pressure. In continuous mode, wall retention is on the average two to ten times higher than desorption, due to the high reionization probability of desorbed species in ICWC discharges, where the electron density is about 10^{18} m^{-3}. Retention can be minimized in pulsed ICWC discharges without severely reducing outpumping. Pulsed He-ICWC discharges have been successfully used on TORE SUPRA to recover normal operation after disruptions, when subsequent plasma initiation would not have been possible without conditioning.

1. Introduction

Wall conditioning is routinely used in fusion devices to control the surface state of the vacuum vessel. It allows reducing plasma impurities and controlling particle recycling, including wall pumping capability and hydrogen isotopic ratio. In today’s facilities, direct current glow discharge conditioning (GDC) in hydrogen or helium is used in the absence of a magnetic field. In ITER, the toroidal magnetic field, generated by superconducting magnets, will be continuously maintained and since GDC are not stable in the presence of high magnetic fields, one can no longer rely on such discharges only, especially between plasma pulses.

Several alternatives to GDC are currently under development, with as most promising candidate Ion Cyclotron Wall Conditioning (ICWC), based on discharges created in the Ion Cyclotron range of frequencies. ICWC was recently added to "Functional Requirements" of the ITER Ion Cyclotron Resonance Frequency (ICRF) system and approved for integration into the ITER baseline [1]. However, new efforts are needed in order to characterize ICWC discharges and optimize their conditioning efficiency, prior to their validation as conditioning process and their application to ITER.

In this paper, recent experimental results on ICWC obtained on current tokamaks are presented: TORE SUPRA (CFC), TEXTOR (fine-grain graphite), ASDEX Upgrade (all W-coated wall) and JET (CFC/Be). First the principle of ICWC, the production of ICRF discharges and their characterization, are presented. The optimization and the assessment of the efficiency of D_2 (or H_2) and He-ICWC discharges for isotopic exchange and fuel removal is the object of a second part. The benefit of pulsed ICWC discharges and its application to recover from disruptions are discussed in a last part.

2. Principle of ICWC, operational parameters and discharge characterization

2.1. Principle

The basic mechanisms of ICRF plasma production for conditioning have been described in [2]. As the RF power is applied to the antenna straps, gas breakdown occurs at the vicinity of the antenna where the oscillating RF electric field $E_{//}$ along the magnetic field lines accelerates single electrons to energies above the ionization threshold at a frequency ω. This phase is considered as the most critical one with respect to the antenna RF voltage and loading due to the fast transition from vacuum to plasma conditions. To avoid deleterious effects in the antenna box, such as arcing, RF voltages/power and RF frequency have to be reduced to technically available minimal values which meet the requirements for RF breakdown.

As the density increases and the electron plasma frequency ω_{pe} becomes of the order of the RF frequency ω, slow wave propagation occurs and the plasma builds up in the whole torus. The coupling of the RF power is non-resonant and the energy is dissipated mostly by collisions [2]. While increasing the plasma density, fast waves start to propagate and plasmas with densities ranging from 10^{16} and 10^{18} m^{-3} (i.e. 4 to 6 orders of magnitude higher than in DC glow discharges) and temperatures $1 < T_e < 10$ eV can be produced in a “relay-race” regime of slow and fast wave excitation [2]. Ion cyclotron heating then occurs in the torus at the major radius R where the resonance frequency of ions equals the wave frequency: $\omega = qB_T(R)/M$, q being the charge of the ion, M its mass and B_T the toroidal magnetic field. In that case, and like in no other low temperature wall conditioning plasmas, fast neutrals, with temperatures above 1 keV and energies up to 50 keV, are created by charge exchange (CX) between the accelerated ions and the background neutral gas.

2.2. Operational parameters

In ITER, the toroidal magnetic field will be permanently maintained either at 5.3 T (D:T phase) or at 2.65 T (He/H phase). With RF frequencies of the ICRH generators ranging from 40 to 55 MHz, 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 ($-1 \leq \rho \leq 1$). Such a scenario can only be simulated in JET for deuterium, with ITER-relevant f/B_T values of 7.0 – 10.5 MHz/T [3], [4] at B_T = 3.3 T and f = 25 MHz, with on-axis $\omega = \omega_{CD^+}$. Similarly, ICR layers for the protons will lie at the same position in ITER under half field conditions. Half field ICWC scenarios have been simulated in ASDEX Upgrade (AUG), as well as in TORE SUPRA and TEXTOR at f/B_T ~15 MHz/T for on axis $\omega = \omega_{CH^+}$. Table 1 gives a summary of the ICWC discharge parameters used in the four tokamaks.

TABLE I: ICWC discharge parameters foreseen in ITER and used in the four tokamaks

	Geometry	PFC	T (K)	R (m)	a (m)	B_T (T)	f (MHz)	P_{RF} (kW)	gas	p (Pa)
ITER (D:T)	Divertor	Be/W	373	6.2	2	5.3	40-55		He, D	
ITER (He H)		Be/C/W				2.65			He, H	
JET	Divertor	C (Be)	373	2.96	1.25	3.3	25	50-250	He, D	10^{-3} - 10^{-2}
AUG	Divertor	W	373	1.65	0.5	2 2.4	30 36.5	10-250	He, H	(1–8) · 10^{-2}
TORE SUPRA	Limiter	C	393	2.4	0.72	3.8 (3.2)	48	25-250	He, H	10^{-2} - 10^{-1}
TEXTOR	Limiter	C	373	1.75	0.47	1.92 (0.23-2.3)	29	15-60	He, H	5.10^{-3} – 5.10^{-2}

2.3. Characterization

ICWC discharges are known to be toroidally homogeneous [5]. However, in the absence of poloidal field, ICWC discharges are usually radially asymmetric and concentrated at the low field side (LFS) [6], with a large density gradient at towards high field side (HFS).

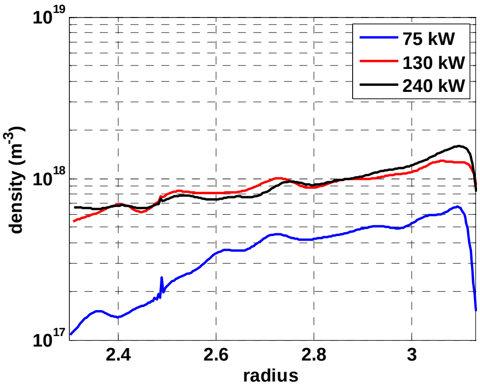

FIG. 1. radial electron density profiles measured by reflectometry in He-ICWC discharges in TORE SUPRA (p=2.10^{-2} Pa).

An illustration can be seen on FIG. 1, where three electron density profiles, measured by reflectometry in pure Helium ICWC discharges on TORE SUPRA (p=2.10^{-2} Pa), are given from the LFS towards the axis. It can be seen that highest densities are measured at the LFS (r = 3.13 m), where the antenna is located, with a radial decay towards the axis (r = 2.38 m). A lower density with a more pronounced decay is observed at low RF power, RF plasma density being proportional to the coupled RF power [6], [7].

Similarly, steep radial profiles of the electron temperature were measured by means of ECE radiometry at the LFS of JET and AUG. Since ICWC discharges are optically thin plasmas, an absolute electron temperature T_e can not be derived from ECE signals. Qualitative profiles of the radiative temperature T_{rad} measured on JET are given on FIG. 2, as a function of time, in a nearly pure D_2 (5%He) ICWC discharge, at $p=5.10^{-3}$ Pa and $P_{RF,coupled}$ =80 kW. Radial asymmetries are explained by ExB drifts [8], [9] and by the fact that fast magneto-sonic wave (FW) is non-propagating in low density ICWC plasmas [10].

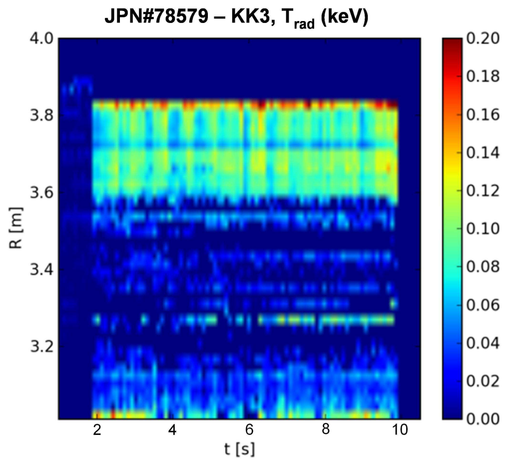

FIG. 2. ECE radiometry measurements in a D_2-5%He ICWC in JET at $p=5.10^{-3}$ Pa and $P_{RF,coupled}$ =80 kW.

3. Optimization of ICWC discharge efficiency

3.1. Homogenization

The ICWC discharge uniformity can be improved by superimposing an additional vertical magnetic field to the toroidal field ($B_V << B_T$). This allows, by tilting the field lines, to elongate the ICWC discharge in vertical direction to top and bottom [11], [12]. A vertical extension of the ICWC discharges towards the bottom of TEXTOR in the presence of B_V could be evidenced by means of Li beam spectroscopy [12]. In JET, the addition of a small B_V (30 mT) to the toroidal field B_T (3.3 T), has resulted in the extension of the ICWC plasma to the divertor area, which could be confirmed by both the line integrated density profiles measured on bottom horizontal and vertical cords at the HFS of the JET interferometer and a higher exhaust during discharge and post-discharge [11].

3.2. Optimization of He-ICWC

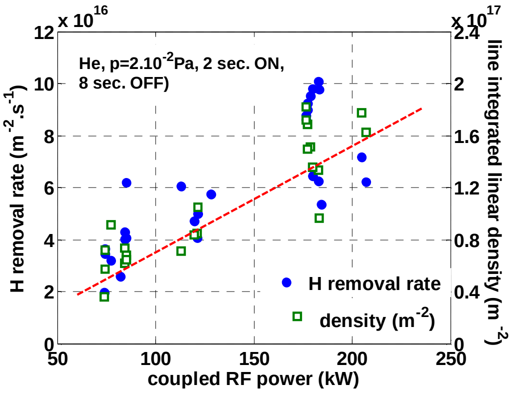

FIG. 3. Dependence of H removal rates and line integrated electron density (green squares, right axis) on coupled RF power in 2s long TORE SUPRA He-ICWC discharges at 2.10^{-2} Pa.

In He-ICWC discharges, D (or H) outpumping is strongly related to the coupled RF power, as shown on FIG. 3, where the H removal rate (blue dots, left axis), measured on TORE SUPRA by means of mass spectrometry, is plotted as a function of the coupled RF power. Removal rates are calculated over 2s active phase and 8s post-discharge. The increase of the removal rate with the RF power to the plasma is consistent with the increase of both the electron (green squares, right axis) and the He^+ densities with the RF power. This also indicates that in He-ICWC discharges, wall desorption is driven by He ion bombardment.

3.3. Optimization of D_2 (or H_2)-ICWC

Efficiency of D_2 (resp. H_2) -ICWC discharge for isotopic exchange has already been reported in [5] and more recently in [13], where a significant modification (from 4 to 50%) of the isotopic ratio H/(H+D) was obtained after nearly 900s He-H_2 ICWC cumulated time on a wall preloaded by D_2-GDC. Fig. 4 shows the modification (from 1 to 20%) of the isotopic ratio [H]/([H]+[D]), measured with a neutral particle analyzer, in three ohmic shots in the all-tungsten ASDEX Upgrade tokamak, before (blue line) and after (red and green lines) nearly 60 sec. cumulated ICWC discharge time.

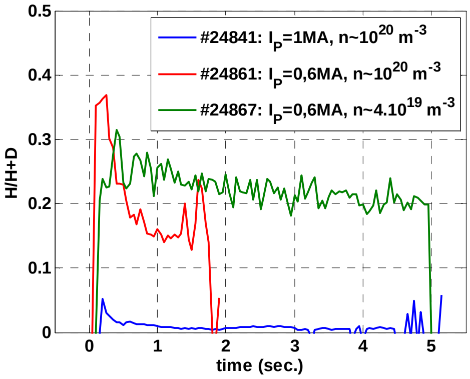

FIG. 4 Isotopic ratio before (blue line) and after (red and green lines) 60 sec. cumulated time He-H_2 ICWC discharge in ASDEX Upgrade (p=5.10^{-2} Pa , various power levels)

However, in continuous H_2 (D_2) ICWC discharges, retention is always measured higher than D (resp. H) exhaust [13]. Strong H pumping of AUG tungsten PFCs during a He-H_2 ICWC discharge (p = 5.10^{-2} Pa, $P_{RF,coupled}$ = 130 kW) was also observed during this experiment [11]. Almost all the hydrogen and an important fraction of the Helium injected were found to be lost at the walls during the ICWC discharge. It is worth mentioning here that He retention was also observed in JET, and attributed to the presence of Beryllium [11].

In JET, the pressure and RF coupled power were adjusted to optimize the efficiency of D_2-ICWC discharges for fuel removal by isotopic exchange. FIG. 5 shows the amount of out pumped H atoms (open black squares) and the outpumping to retention ratio (red dots, right axis) as a function of the D_2-ICWC pressure for 150 < $P_{RF,coupled}$ < 250 kW. The release of H atoms was found to increase with the D_2 partial pressure in the discharge, in agreement with similar increase of D outpumping in H_2-ICWC on TORE SUPRA in a higher pressure range (up to 8.10^{-2} Pa) [13]. The best conditions to maximize the ratio between outpumping and retention (red dots on FIG. 5) without lowering the H release were found to be high power (~250 kW) and low pressure (~2.10^{-3} Pa). With these parameters, the isotopic ratio could be changed from 20% to 50 % after 72 sec. cumulated D_2-ICWC discharge time on JET walls preloaded with H_2-GDC [11]. The gas balance from gas chromatography yield 1.6.10^{22} H out gassed, which is to be compared with the short term retention accessible by plasma operation: 2.10^{23} D atoms [14].

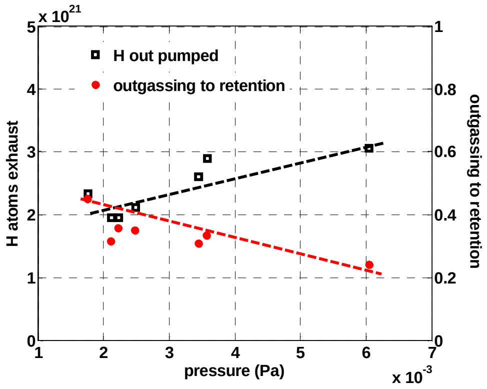

FIG. 5. H exhausted (open black squares, left axis), and outpumping to retention ratio (red dots, right axis) as a function of the D_2 pressure for a series of JET discharges with $P_{RF,coupled}$ > 150 kW.

4. Pulsed discharges

4.1. Influence of the pulse duration

Due to the relatively high density in ICWC plasmas (typically 4 orders of magnitude larger than in glow discharges), wall desorbed particles have a high probability to undergo ionization or dissociation and to be subsequently lost to the walls before being pumped out. Their residence time in the discharge is much smaller than their characteristic pumping time τ_S [2] and consequently one can write the out pumped flux as a function of the wall desorbed flux: $Q_{outpumped} = (1 - f)\, Q_{desorbed}$, with f the above mentioned probability $f = \tau_i^{-1} / (\tau_S^{-1} + \tau_i^{-1})$ ~1. Such a high reionization probability can explain low out pumping efficiency and high particle retention during the RF pulse [15]. Reionization of desorbed species, and finally particle retention, are only present when the RF power is on.

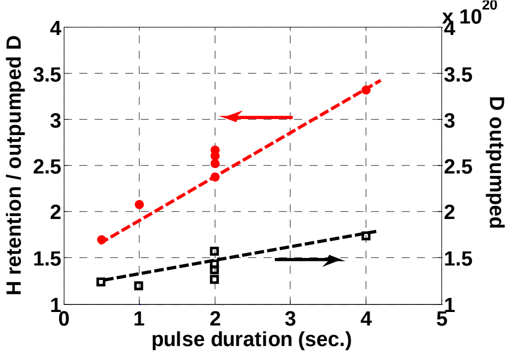

FIG. 6. D outpumping (black, right axis) and ratio of retained H over D outpumping vs. pulse duration in TEXTOR H_2-ICWC discharges ($P_{RF,generator}$~100 kW, p ~10^{-2} Pa)

Short ICWC discharge pulses, followed by a pumping time, have to be used to reduce retention over a discharge and post-discharge cycle. In the post-discharge, only wall desorption occurs with a characteristic time scale (of the order of 1–10 s) depending on the physical process. In order to optimize the fuel removal efficiency, the influence of the pulse duration on the outpumping was studied on TORE SUPRA and TEXTOR in both H_2-ICWC and He-ICWC discharges. Results obtained on TEXTOR are shown on FIG. 6 for the removal of D by H_2-ICWC discharge on walls saturated by a D_2-GDC. Clearly, the lowest ratios between retention and outpumping (red dots, left axis) are obtained for the shortest the pulse durations.

The total amount of exhausted D with the discharge time, calculated over a complete cycle (discharge and post-discharge), with a post-discharge duration fixed to 30s, and given by the black squares dots on FIG. 6 (right axis), is also decreasing as the RF ON time decreases, but two times slower than the retention to outpumping ratio. Similar results were obtained on TORE SUPRA [11].

4.2. Recovery from disruption using pulsed ICWC

Pulsed He-ICWC discharges ($p = 4.10^{-2}$ Pa, $P_{RF,coupled} = 60$ kW) have been successfully applied on TORE SUPRA to recover normal operation after disruptions, when subsequent plasma initiation would not have been possible without conditioning.

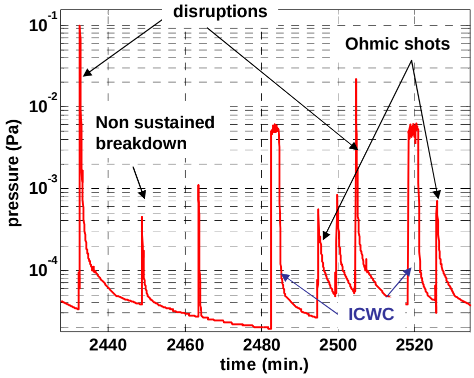

FIG. 7. Total pressure in TORE SUPRA as a function of time illustrating recovery from two disruptions.

Two disruptions were provoked on the outboard poloidal limiter during an ohmic shot at a plasma current I_P=1,2 MA. The current decay rate in both disruptions was equal to 360 MA/s. The total pressure in the vacuum chamber is shown in FIG. 7. 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 during the pulsed He-ICWC discharge was found comparable with those obtained during Taylor Discharge Conditioning discharges (low current ohmic pulsed discharges) [16], which are routinely used on TORE SUPRA to recover from disruptions. The removal rates of HD molecules were typically $Q_{HD} \sim 1\text{-}2.10^{16}$ mol.m^{-2}.s^{-1} at low RF power [13].

5. Conclusion

Ion Cyclotron Wall Conditioning is a promising option for in between pulses wall conditioning in future superconducting devices, such ITER. ICWC discharges were studied on JET, ASDEX Upgrade, TORE SUPRA and TEXTOR. Among others, reflectometry and ECE radiometry were used to characterize these low density and temperature plasmas. The observed radial and poloidal inhomogeneities can be corrected with the help of small radial and/or vertical magnetic fields, resulting in a vertical extension confirmed on TEXTOR and JET.

In He-ICWC, fuel removal is driven by Helium ion bombardment. Significant He retention is reported in both AUG and JET, a known issue in the latter case.

The isotopic ratio H/(H+D) was changed from 1 to 20% after nearly 60s He-H_2 ICWC cumulated time in H_2-ICWC discharge in the all-tungsten tokamak ASDEX Upgrade, in agreement with results obtained on TORE SUPRA and JET. D_2-ICWC discharges efficiency has been optimized in JET, with the double aim to maximize outpumping and to minimize retention caused by the reionization of wall desorbed particles. An amount of H atoms equivalent to 10% of the short term retention could be removed from JET walls.

Pulsed ICWC discharges allow to minimize retention to outpumping ratio in D_2 (or H_2) ICWC, without severely decreasing the isotope exchange efficiency. Such a very promising operation mode may be used in the superconducting tokamak ITER, and could allow exchanging tritium by deuterium efficiently without saturating walls. Pulsed He-ICWC discharges were successfully applied in TORE SUPRA to recover to normal operation after disruptions.

Acknowledgments

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