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Isotope Exchange by Ion Cyclotron Wall Conditioning on JET

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ABSTRACT

The isotopic exchange efficiencies of JET Ion Cyclotron Wall Conditioning (ICWC) discharges produced at ITER half and full field conditions are compared for JET carbon (C) and ITER like wall (ILW). Besides an improved isotope exchange rate on the ILW providing cleaner plasma faster, the main advantage compared to C-wall is a reduction of the ratio of retained discharge gas to removed fuel. Complementing experimental data with discharge modeling shows that long pulses with high (but still safe) ICRF power maximizes the wall isotope removal per ICWC pulse. In the pressure range 1 to 7.5×10^{-5} mbar, the removal efficiency reduces with increasing discharge pressure. As most of the isotopes are recovered in the post discharge phase, duty cycle optimization studies for ICWC on JET-ILW need further consideration. The accessible reservoir by H₂-ICWC at ITER half field conditions on the JET-ILW preloaded by D₂ tokamak operation is larger than 7.3×10^{22} hydrogenic atoms, and may be exchanged within 400s of cumulated ICWC discharge time.

1. INTRODUCTION

Ion cyclotron wall conditioning (ICWC) is a well-studied discharge wall conditioning technique for fusion devices applied in the presence of nominal toroidal magnetic fields [1,2,3]. Recent experiments on JET assessed ICWC for isotope exchange on the ITER-like wall (ILW) equipped with Be main chamber and W divertor ([4]) and compared the efficiency to earlier experiments with the JET-CFC wall. This contribution presents an overview of these experiments with focus on (i) ICWC discharge characterization both at ITER full field and half field scenario, (ii) investigating the accessible fuel reservoir by ICWC from particle balance analysis on JET-C and JET-ILW as well as (iii) optimizing the fuel removal efficiency. Long-term fuel retention with JET-ILW was already shown to be at least ten times lower than in JET-C whereas the accessible reservoir near the surface, reflected in the shortterm retention, is expected to be in the same range [5].

Isotope exchange conditioning discharges aim at replacing hydrogen isotopes stored in the near surface (<100 nm), which is required to control the plasma isotopic ratio of tokamak discharges. The isotopic exchange efficiency is expressed as the rate at which a technique can change the isotopic ratio of the walls and the total extra retention it causes. Isotopic exchange experiments on JET are especially motivated by the need for assessing the exchange efficiency on the JET-ILW as well as JET's unique possibility to simulate D₂-ICWC in ITER full field conditions.

2. EXPERIMENTAL SETUP

The use of ICWC during the non-active operation phase (H plasmas) and active phase (D and D:T plasmas) of ITER implies fixed toroidal field values of respectively half ($B_0 = 2.65\text{T}$) and full (5.3T) nominal magnetic field. Operating the JET antennas at 25MHz with toroidal field values of respectively $B_0 = 3.3\text{T}$ and 1.65T simulates on JET the ITER full (5.3T/40MHz) and half (2.65T/40MHz) field case with on axis location of fundamental D⁺ (resp. H⁺) resonance layer. A

small vertical magnetic field with field lines following the curvature of the inner and outer main chamber plasma facing components (PFC) is applied with amplitude optimized for maximal poloidal homogeneity ($B_v/B_0 = 8 \times 10^{-3}$) [6].

Three separate JET experiments were performed: (i) ITER full field D₂-ICWC^I with cryopumping on H₂-GDC preloaded C-wall, (ii) ITER full field D₂-ICWC^{II} with turbo-pumping on H₂-GDC preloaded ILW and (iii) ITER half field H₂-ICWC^{III} with turbo-pumping on naturally D₂ preloaded ILW. Throughout the text the experiments are labeled by superscripts ^{I, II & III} for clarity. The JET A2 antennas operated in plasma production mode with monopole phasing, coupling 50 to 240kW to low density ICRF plasma $0.3-3.4 \times 10^{17} \text{ m}^{-2}$. Preprogrammed gas injection using either a midplane gas injection module located toroidally opposite to the operated RF antennas or divertor gas injection modules when operating all 4 A2 antennas simultaneously resulted in discharge pressures of $0.3-7.5 \times 10^{-5} \text{ mbar}$. Table 1 summarizes the discharge parameters.

Particle balances are obtained via (i) pressure recordings in the gas injection modules, (ii) residual gas analysis using (iia) pulse based mass spectrometry and penning gauge spectroscopy in ducts connected to the divertor, and (iib) gas chromatography of the total pumped gas after each of the experiments^{I, II, III}. The evolution of the wall isotopic ratio is indirectly monitored via the plasma isotopic ratio from characteristic H and D (beta) radiation in the low temperature plasma.

The plasma and wall flux characterization in this paper relies on (i) poloidal HCN interferometry viewing lines, (ii) low energy neutral particle analyser (NPA) measuring the energetic charge exchange (CX) neutral spectral flux (5-50keV) along a radial line of sight (iii) penning gauge pressures and (iv) RF signals for coupled power calculation. Experimental data are complemented by 0D plasma modelling (TOMATOR code [7]) solving energy and particle balance equations for hydrogen atomic and molecular plasma species, taking into account (1) elementary atomic and molecular collision processes, (2) RF heating of electrons and protons, (3) particle and energy confinement, as well as (4) wall flux recycling, active pumping and gas injection.

3. DISCHARGE CHARACTERIZATION

3.1 PLASMA DENSITY

Pulse averaged interferometry densities measured along radial line of sight for D₂-ICWC^I on JET-C are shown as function of scaling $P \cdot p^n$ on Fig. 1a. Within the pressure (p) and coupled power (P) range of $p = 1.0$ to $4.0 \times 10^{-5} \text{ mbar}$ and $P = 50$ and 260 kW (including preparatory pulses not included in Table 1), the densities vary over 1 order of magnitude from 0.2 to $2.3 \times 10^{17} \text{ m}^{-3}$ and are fitted with good correlation, $R = 0.79$, using power $n = -1/3$. The density scaling for the same pressure and power range is confirmed by 0D ICRF plasma simulations [7] (correlation coefficient $R > 0.99$) using fixed coupled power fraction to electrons and atomic ions of resp. 0.9 and 0.1 , based on JET ICWC RF coupling studies [1], and using fixed charged particle confinement time of 5 ms . The latter poor confinement is motivated considering the typical simple toroidal magnetic field geometry used for ICWC, characterized by a radial gradient and toroidal curvature, as well as gradients in electron

density and temperature which together are known to drive electrostatic instabilities [8]. This enhanced transport (order of magnitude larger than Bohm diffusion) in large devices for the large toroidal field values (1.65-3.3T) combined with low ion and electron temperatures is presently a field of study.

For D_2 -ICWC^{II} pulses on JET-ILW, having modest coupled power variations (140-180kW), the density of the higher-pressure pulses ($2.3 \pm 0.2 \times 10^{-5}$ mbar) matches the predicted (JET-C^I fit) density within a factor 1.4. In agreement with numerical simulations for pressures below 0.5×10^{-5} mbar, the remaining pulses at significantly lower pressure ($0.5 \pm 0.2 \times 10^{-5}$ mbar) deviate strongly from the $p^{-1/3}$ scaling. The measured density ranges from 3 to $8 \times 10^{16} \text{ m}^{-2}$. Determining the pressure-density relation for these low density pulses is compromised by drift of the zero-point and low signal to noise ratio in the interferometry data.

No interferometry data was obtained for the H₂-ICWC^{III} pulses. It is expected that the density of these pulses with pressure range of 1.4 to 7.5×10^{-5} mbar and power range of 100 to 200kW can be successfully modeled with the JET-C^I-fit, leading to a similar density range of 0.5 to $1.5 \times 10^{17} \text{ m}^{-3}$. It is noted that the likely lower confinement at half field may reduce the values.

3.2 WALL FLUX COMPONENTS

Fundamental in the study of discharge wall conditioning techniques is characterizing the particle fluxes to the vessel first wall. In section 4 the fluxes will be brought in relation to the conditioning efficiency. Simulated for JET-ILW H₂-ICWC^{III} pulses, using the simulation parameters from the previous paragraph, one distinguishes (i) a low energy hydrogen atom flux of 1 to $5 \times 10^{20} / \text{m}^2 \text{ s}$ with energies between 3 and 5eV determined by Franck Condon energy upon dissociation and increased by elastic collisions with ions, and a (ii) low energy (atomic) hydrogen ion flux of 0.5 to $2.5 \times 10^{19} / \text{m}^2 \text{ s}$. It is expected that the high neutral flux enhances surface recombination and hence wall desorption. As neutrals are not constrained by the magnetic field, the neutral flux can be considered homogeneous, reaching also remote areas. For the ion flux it was shown that sheaths affect the ion impact energy on the wall to about 10–50eV [9]. As ions are transported along the magnetic field lines, the ion flux on JET is likely inhomogeneous, being highest on first limiting surfaces such as antenna protection limiters and inner bumpers. On ITER, designed with a shaped first wall, the ICWC ion-wetted area approaches the total surface area.

The simulated low energy ion wall flux for JET is found to scale as $P \cdot p^{-1/3}$ ($R > 0.99$) and is thus directly proportional to the electron density, which is understood from the chosen fixed charged particle confinement time. The simulated low energy neutral atom flux on the other hand scales as $P \cdot p^{+1/3}$ ($R > 0.99$), which is proportional to $n_e \cdot p^{+2/3}$.

A third wall flux component consists of (iii) energetic neutrals stemming from CX reactions with the minor energetic plasma ion population ($> 1 \text{ keV}$) produced by resonant ICRF absorption, and evidenced by NPA diagnostic. The fast CX flux measured on JET is of the order of 1×10^{15} to $1 \times 10^{17} / \text{m}^2 \text{ s}$ with Maxwellian energies of 1 to 10keV. While the high CX flux energies are sufficient to reach deeper surface layers and to cause physical sputtering, the flux was shown previously to

have limited conditioning contribution in JET isotopic exchange ICWC discharges [6]. Energetic ion species produced by local resonant absorption are not described in the 0D plasma model. Wall flux energies below 1keV remain presently undiagnosed on JET and require further study.

4. ISOTOPE EXCHANGE EFFICIENCY

4.1 PARTICLE BALANCE

Table 1 summarizes the particle balances as obtained from gas injection data and chromatography analysis of the total pumped amount of gas. Within the limited number of RF pulses for D₂-ICWC^I on JET-C it was possible to remove 1.6×10^{22} hydrogen particles (= about 6 monolayers) from the GDC preloaded wall, corresponding to approximately 10% of the short term retention in JET-C accessible by plasma operation (2×10^{23} atoms, [10]). For JETILW, thought to have a smaller accessible fuel reservoir in tokamak discharges than JET-C ($< 1 \times 10^{23}$ atoms [11]), D₂-ICWC^{II} on the H₂-GDC preloaded wall removed 2.9×10^{22} H atoms within a similar total RF discharge time. On increasing the later RF discharge time to 206s, for H²-ICWC^{III} on JET-ILW, the amount of recovered atoms from the naturally loaded wall increases accordingly to 6.2×10^{22} D atoms, approaching complete depletion of the wall loaded hydrogen isotope. No/limited extra wall retention is observed in the JET-ILW pulses (last row of Table 1), whereas retention was about 3 times larger than removal in JET-C. In section 4.3 the removal efficiencies are studied as a function of discharge parameters. Retention dependencies are discussed only for the JET-C pulses.

4.2 ISOTOPIC EXCHANGE

Figure 2 (left axis) reflects the progressing change-over of the wall isotopic ratio via the plasma isotopic ratio obtained from H and D beta radiation spectra along a vertical viewing line looking into the divertor measured by the same diagnostic for all 3 sets of pulses. A clear difference between JET-CI and JET-ILW^{II,III} pulses is the lower initial plasma isotopic ratio. The initial wall isotopic ratio as sampled by D₂-tokamak discharges after wall pre-loading for JET-ILW^{III} experiment is less than 2% on the figure scale. The wall preloading procedure for D₂-ICWC on JET-C^I and JET-ILW^{II} was identical. While cryo-pumps were used in JET-C^I pulses and turbo pumps in JET-ILW^{II,III} pulses, the plasma facing components are thought to be the main cause for this difference, e.g. via a higher wall isotope release yield (~5 times) on JET-C^I wall compared to JET-ILW^{II,III}.

Figure 2 (right axis), plotting the cumulated sum of the removed wall isotopes as a function of the total RF time, integrating each time over discharge and post discharge up to the start of the next pulse, illustrates that the removal (by pumps) is about two times faster for JET-ILW^{II,III} than for JET-CI (see as well Table2). The possible higher yield for JET-C^I is counter balanced by the poor ratio of net retention over removal. No clear difference for D₂-ICWC_{II} at full field and H₂-ICWC^{III} at half field appears from these results.

Although the plasma isotopic ratio remains stable after ~60s of discharge time, the cumulated amount of pumped wall isotopes shows no sign of saturation yet. The accessible fuel reservoir is

clearly larger than the removal achieved within 206s. It is expected that the limits of efficient wall isotope removal may become clearer on doubling the total discharge time.

4.3 PARAMETRIC DEPENDENCIES

a. Removal as function of coupled power, pulse length and wall isotope concentration

Isotope exchange efficiency optimization requires revealing main removal dependencies on discharge parameters. Figure 1b shows for all 3 experiments the removed amount of wall isotopes as function of the product of coupled RF power P , pulse length Δt and wall isotope concentration N_w , reflecting the simple relation $dN_w/dt = f(P, p, \dots)N_w$. For D_2 and H_2 -ICWC on JET-ILW^{II,III} the removal is strongly dependent on the loaded wall isotope concentration, significantly changing from pulse to pulse, as well as on the discharge duration ($R = 0.87$ and 0.86 for resp. D_2 ^{II} and H_2 ^{III}-ICWC). For JET-C^I pulses with constant pulse length and limited wall isotope depletion the dependency is largely determined by the coupled power ($R = 0.90$). Each of the plots assumes a preset initial accessible wall isotope concentration; A correlation above 85%, requires (i) for JET-C^I setting the total amount of removed wall isotopes lower than 25% of the initial concentration and (ii) a removal of more than 67% of initial H for the D_2 -ICWC^{II} experiment on JET-ILW, while for (iii) the H_2 -ICWC^{III} pulses on JET-ILW the optimal correlation is 0.85 when assuming that 85% of the initial D is removed.

b. Removal as function of density and pressure

Wall isotope removal efficiency for the higher pressure pulse sets (D_2 -ICWC^I on JET-C and H_2 -ICWC^{III} on JET-ILW), respecting common density scaling $n_e \sim P.p^{-1/3}$ defined for pressures above 1×10^{-5} mbar (section 3.1), is studied as function of density in Fig. 1c. For the D_2 -ICWC^I pulses on JET-C removal correlates maximally ($R = 0.93$) with the square root of the density. Verifying with H_2 -ICWC^{III} on JET-ILW, plotting removal as function of $\sqrt{n_e} \cdot \Delta t \cdot N_w$ (Fig. 1c) retains as well a good correlation ($R = 0.80$). This indicates that indeed the ion flux, being proportional to density, rather than the higher -low energy- neutral flux, strongly depending on pressure as well (see section 3.2), is responsible for the wall conditioning efficiency.

c. Retention on JET-C

Due to absence of or limited additional retention no clear parametric retention dependencies were found for JET-ILW ICWC^{II,III} pulses. In agreement with observations on C-TORE SUPRA and TEXTOR [12], the on JET-C observed net-retention seems mainly due to an initially incomplete transient (=accessible) reservoir loading, which is typically observed in first of series ICWC discharges. The net retention per pulse being strongly proportional to the (inverse of the) wall loading ($R > 0.90$), no clear dependencies on power, density nor pressure was found. The discharge length for each of the pulses was practically constant. Modelling of partial pressures in C-TORE SUPRA ICWC discharges discussed in [13] learned that while most of the wall flux is transiently stored, remaining accessible, a small though significant part is stored permanently (codeposits, remote areas, ...) which in the continuous fast process of particle recycling leads to significant net retention.

5. DISCUSSION AND CONCLUSIONS

JET ICWC discharges, reliably produced at ITER half^{II} and full field^{I,II} conditions, have shown the ability to change the wall isotopic ratio of JET-C^I and JET-ILW^{II,III} within limited number of discharges. The presented analysis based on complementing experimental data with 0D discharge modeling concludes that for maximizing the wall isotope removal per ICWC discharge one has to aim at long pulses with high (but still safe) RF power. For pressures above 1×10^{-5} mbar, the removal efficiency reduces with increasing pressure. Besides the improved ICWC isotope exchange rate on ILW^{II,III} providing a cleaner plasma faster, the main advantage compared to CFCI is a reduction of the ratio of retained discharge gas to removed fuel, equal to ~ 3 for C-wall^I and 0.86–1.4 for the ILW^{II,III}. As most of the isotopes are recovered in the post discharge phase (high outgassing pressure peak followed by slow pressure decay (See e.g. [14]), duty cycle optimization studies for ICWC on JET-ILW still need further consideration.

The accessible fuel reservoir by H₂-ICWC on JET-ILW^{III} preloaded by D₂ tokamak operation is found to be larger than 7.3×10^{22} hydrogenic atoms. This number is $\sim 2 \times$ larger than presently achieved in isotope exchange experiments by limiter plasmas [9]. The certainty of the parametric dependencies at base of the ICWC estimations has to be improved via further experimentation, though a close to complete isotopic change over by ICWC may be expected after 400s of cumulated discharge time.

The high removal without net retention on JET-ILW indicate that the ICWC wall fluxes in the presented experiments^{II,III} feature inefficient beryllium erosion and redeposition in contrast to limiter plasmas [9], though the fuel inventory of beryllium deposits, predominantly located on main wall and at the top of the inner divertor [15], may be accessed. Possibility of complementing limiter plasmas with ICWC for fuel recovery after D:T pulses on ITER requires further investigation.

Further ICWC studies on JET-ILW should envisage (i) increased exposure time, (ii) determining the dominating plasma wall interaction areas, which are at present most likely the berillium main wall, (iii) increasing the accessible reservoir by discharge homogeneization and (iv) diagnosing the lower energetic ion population (< 1 keV).

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	JET-C D ₂ -ICWC ^I 3.3T – 25MHz	JET-ILW D ₂ -ICWC ^{II} 3.3T – 25MHz	JET-ILW H ₂ -ICWC ^{III} 1.65T – 25MHz
Vacuum pumping	Cryopumps	Turbopumps	Turbopumps
Wall preloading	H ₂ -GDC	H ₂ -GDC	D ₂ plasma op.
Pressure [$\times 10^{-5}$ mbar]	1.3 – 1.6	0.3 – 2.5	1.4 – 7.5
ICRF coup. power [kW]	50 - 240	140 - 180	100 - 200
# pulses, pulse length	8 \times 8sec	19 \times (2 – 8)sec	21 \times (2 – 20)sec
Total discharge time	~60s	~65s	~220s
(a) Recovered atoms ($\times 10^{22}$)	1.6 H	2.9 H	6.2 D
(b) Retained atoms ($\times 10^{22}$)	4.8 D	2.5 D	8.6 H
Ratio (b) to (a)	3.0	0.86	1.4

Table 1: Overview experimental conditions and particle balance for three JET ICWC isotopic exchange experiments, labelled I, II and III.

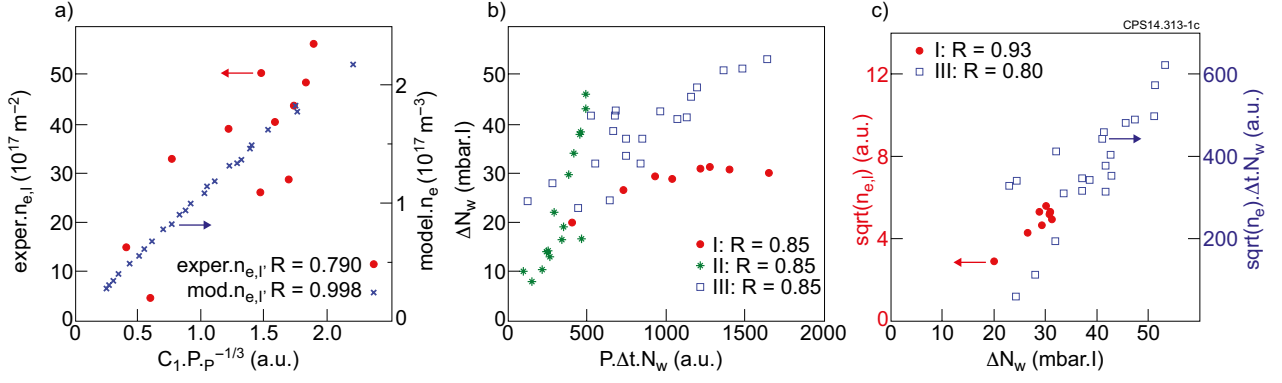


Figure 1: Parametric dependencies for ICWC isotopic exchange discharges on $JET-C^I$ and $JET-ILW^{II,III}$ (discharge parameters for labels I, II & III are given in Table 1, R is correlation coefficient). a) Density for D_2 -ICWC^I on $JET-C$ as function of coupled RF power P and pressure p . Left axis: pulse averaged radial interferometry densities $n_{e,i}$; Right axis: 0D modeled density n_e for pressure and powers of $JET-ILW$ H_2 -ICWC^{III} pulses. b) Removed amount of wall isotopes ΔN_w as function of coupled RF power P , pulse length Δt and wall isotope concentration N_w for exp. I, II and III. c) Density dependency of removal for exp. I (left axis) and III (right axis). Densities of III (right axis) are estimated from scaling $P/p^{1/3}$.

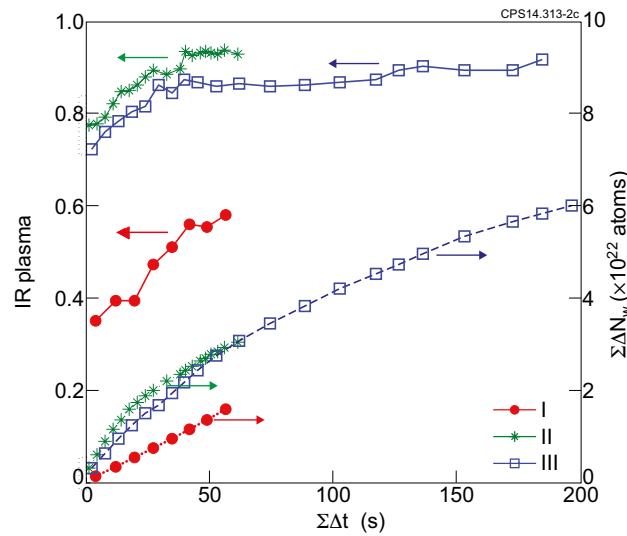


Figure 2: Isotopic exchange by ICWC as function of cumulated discharge time ($\Sigma \Delta t$) on $JET-C^I$ and $JET-ILW^{II,III}$ (discharge parameters for labels I, II & III are given in Table 2). Left axis: averaged plasma isotopic ratio (IR_{pl}) per discharge obtained from H and D beta radiation; Right axis: cumulated sum of the removed wall isotopes $\Sigma \Delta N_w$.