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Self-consistent application of ion cyclotron wall conditioning for co-deposited layer removal and recovery of tokamak operation on TEXTOR

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Abstract

This paper presents a demonstration experiment of ion cyclotron wall conditioning (ICWC) on TEXTOR covering all ITER wall conditioning aims and discusses the implications for ITER. O₂/He-ICWC applied to erode carbon co-deposits removed 6.6×10^{21} C-atoms (39 pulses, 158 s cumulated discharge time). Large oxygen retention (71% of injected oxygen) prevented subsequent ohmic discharge initiation. Plasma operation was recovered by a 1h47 multi-pulse D₂-ICWC procedure including pumping time between pulses with duty cycle of 2 s/20 s, cleaning the vessel from oxygen impurities, followed by a 23 min He-ICWC procedure (2 s/20 s), applied to desaturate the deuterium-loaded walls. A stable ohmic discharge was established on the first attempt right after the recovery procedure. The discharges showed improved density control and only slightly increased oxygen characteristic radiation levels (1–1.5 times). After the recovery procedure 36% of the injected O-atoms remained retained in the vessel, derived from mass spectrometry measurements. This amount is in the estimated range for storage in remote areas obtained from surface analysis of locally exposed samples. The removed amount of oxygen by D₂ and He-ICWC obtained from mass spectrometry corresponds to the retention in plasma-wetted areas estimated by surface analysis. It is concluded that most of the removed oxygen stems from plasma-wetted areas while shadowed areas, e.g. behind poloidal limiters, may feature net retention of the discharge gas. On ITER, designed with a shaped first wall, the ICWC plasma-wetted area will approach the total surface area, reducing consequently the retention in remote areas. A tentative extrapolation of the carbon removal on TEXTOR to tritium removal from co-deposits on ITER in the 39×4 s O₂/He-ICWC discharges, including pumping time between the RF pulses, corresponds on ITER to a tritium removal in the order of the estimated retention per 400 s DT-burn (140–500 mgT (Shimada and Pitts 2011 *J. Nucl. Mater.* **415** S1013–6)).

(Some figures may appear in colour only in the online journal)

1. Introduction

Discharge wall conditioning is an effective tool to improve plasma performance in tokamak and stellarator fusion research devices by (i) reducing the generation of plasma impurities liberated from the wall and (ii) controlling the recycling of

hydrogenic fluxes. On ITER discharge wall conditioning will be employed as well for (iii) mitigating the tritium inventory build-up, for which one relies mostly on the removal of tritium-rich co-deposited layers. On carbon devices, it is known that the use of the reactive gas oxygen, either pure or oxygen/helium mixtures, is especially efficient for the removal of carbon

Table 1. Oxygen balance: overview of the pumped gases measured by mass spectrometry during O₂/He-ICWC and the recovery D₂ and He-ICWC procedure given in number of (#) atoms or molecules, counting both ¹⁶O and ¹⁸O (chronology is given in figure 1). The negative values are calculated as removed minus injected oxygen.

Unit # at./mol.	O ₂ /He- ICWC	Between sessions	D ₂ - ICWC	He- ICWC	Total balance
O-atoms	-2.6×10^{22}	9.3×10^{21}	3.9×10^{21}	1.6×10^{20}	-1.3×10^{22}
CO	5.8×10^{21}	1.4×10^{21}	1.2×10^{21}	3.1×10^{19}	8.4×10^{21}
CO ₂	7.8×10^{20}	4.2×10^{20}	2.2×10^{20}	1.4×10^{19}	1.4×10^{21}
Water	8.4×10^{20}	7.0×10^{21}	2.3×10^{21}	1.2×10^{20}	1.0×10^{22}

operation from this severely deteriorated wall purity state needs to be demonstrated. The ICWC procedure to achieve this consisted of 1h47 of multi-pulse D₂-ICWC and 23 min of multi-pulse He-ICWC. ICWC pulses of 2 s were repeated every 20 s maintaining constant discharge parameters. In total 322 D₂-ICWC pulses were performed at a steady-state low magnetic field ($B_T = 0.23$ T), of which 210 were with feedback controlled D₂ pressure ($p_{D_2} = 5 \times 10^{-4}$ mbar), using both antennas at $f_{RF} = 29$ MHz and $P_{RF,A1\&A2} = [2 \times 50$ kW (260 pulses), 2×100 kW (60 pulses)]. To desaturate the deuterium-loaded walls prior to the ohmic tokamak plasma operation, an additional 67 He-ICWC pulses were applied respecting the same RF duty cycle, magnetic field, antenna frequency, pressure and power ($P_{RF,A1\&A2} = 2 \times 50$ kW). From the insignificant heating of the antenna structure, the absence of RF trips and metallic characteristic radiation, it was concluded that the RF systems worked safely and reliably throughout the whole conditioning procedure.

Two standard ohmic discharge attempts after the conditioning procedure were both successful, featuring good density control and proving the recovery of TEXTOR operation, as will be shown in section 4.

3. Oxygen balance

3.1. Mass spectrometry

An estimate for the oxygen particle balance is obtained via mass spectrometry, and a summary is given in table 1. From the carbon removal during O₂-ICWC a figure of merit is derived for the achievable T-removal on ITER in the next section. Working with oxygen-18 as the discharge gas enabled the use of the low background mass spectrometry signals for C¹⁸O (mass 30) and C¹⁸O₂ (mass 48) and presented an unambiguous marker for surface analysis. Nevertheless, for the oxygen balance, the injected amount of oxygen needs to be compared with the total removed amount of oxygen isotopes. As such the ¹⁸O₂-discharges can be considered to effectuate oxygen isotopic exchange on the TEXTOR wall, which is relatively abundantly loaded with ¹⁶O. The latter abundance is illustrated by the stable isotopic ratios throughout the experiment, estimated from the high mass spectrometry signals for C¹⁶O and C¹⁸O, as well as for the weaker C¹⁶O₂ and C¹⁸O₂ signals (masses 28, 30, 44 and 48, respectively) taken in the outgassing peak after the ICWC discharge termination, shown in figure 2(b).

The oxygen-18 consumption in the 39 O₂/He-ICWC discharges amounted to 3.6×10^{22} O-atoms, decaying over 15 discharges from about 2.3×10^{21} atoms/discharge in the first 3 discharges to 7.7×10^{20} atoms/discharge in the last 20 discharges (shown in figure 2(a)). This typical initial

Figure 2. (a) Oxygen balance of the O₂/He-ICWC discharges for co-deposited layer removal. The oxygen retention in TEXTOR saturates after 60 s of plasma, reaching an equilibrium between retention and recovery. (b) The oxygen isotopic ratio of the wall-desorbed gas after ICWC discharge termination remains stable around 60% indicating the abundant presence of ¹⁶O in TEXTOR.

wall saturation effect has been observed as well in H₂-ICWC discharges in TEXTOR [5, 7]. Where the oxygen consumption remained stable only about 30% of the injected oxygen could be recovered, mostly as CO and CO₂. In total, $7.3 \pm 1.8 \times 10^{21}$ oxygen atoms were pumped as CO or CO₂ (both ¹⁶O and ¹⁸O) while 2.2×10^{21} O-atoms were removed as O₂, and only 8.4×10^{20} O-atoms as water (including isotopes H, D, ¹⁶O and ¹⁸O), as derived from mass spectrometry measurements. This high removal of O as CO and CO₂ (70%) is in agreement with previous reports on TEXTOR O₂-ICWC discharges [3]. The errors of the mass spectrometry analysis are considerable, estimated to up to 25% for CO and CO₂ and possibly higher for H₂O solely due to incomplete calibration data. The calculated partial pressures are consistent with the total pressures.

After the O₂/He-ICWC operation 71% of the injected O-atoms remained retained in the wall (2.6×10^{22}). Between the two experimental days the partial pressures were continuously monitored. The partial pressures in this period corresponded to a removal of 2.2×10^{21} O-atoms as CO and CO₂, and a significant amount of 7.0×10^{21} O-atoms in the form of water. About 50% of these molecules were retrieved during

the standard nightly heating of the liner (45 min at 300 °C). The remaining retained oxygen at the start of the D₂ and He-ICWC recovery procedure equalled 1.7×10^{22} O-atoms, or 47% of the injected amount. The non-sustained ohmic breakdowns preceding the recovery ICWC discharges indicate that this amount is too much to allow the ohmic start-up. The discharge attempts themselves removed a negligible amount of oxygen: 0.1×10^{18} O-atoms as CO and CO₂, 1.7×10^{19} O-atoms as water.

The majority of the retrieved oxygen in the recovery wall conditioning procedure was pumped during the 1h47 multi-pulse D₂-ICWC procedure: in total, 2.3×10^{21} water molecules and an expected lower amount of 1.6×10^{21} O-atoms as CO and CO₂. The 23 min multi-pulse He-ICWC procedure, aimed at desaturating the walls of hydrogen isotopes to ensure successful ohmic start-up and good density control, removed 1.6×10^{20} O-atoms.

At the end of the recovery procedure still 1.3×10^{22} O-atoms remained retained in the wall. This corresponds to 36% of the injected amount, or 49% of the initially retained O-atoms.

3.2. Surface analysis

Radial profiles of ¹⁸O deposition were taken from exposed cut-outs from TEXTOR DED tiles (carbon) on the midplane holder and several aluminum- and carbon-coated silicon samples on the limiter-locks using the ¹⁸O(p, α)¹⁵N nuclear reaction at 2 MeV. The samples were exposed in the range $r = 45\text{--}53$ cm with the TEXTOR poloidal limiters being at $r = 47.5$ cm. Around this radius ($r = 47\text{--}48$ cm) an average of $(11.7 \pm 5.7) \times 10^{15}$ ¹⁸O cm⁻² was found on a DED sample parallel to B_T , while on shadowed areas ($r = 50\text{--}53$ cm) deposition concentrations ranging from 5.6×10^{15} to 29×10^{15} ¹⁸O cm⁻² were found. On an aluminum-coated sample from the top limiter-lock a lower deposition of $2.8 \pm 0.5 \times 10^{15}$ ¹⁸O cm⁻² at $r = 47$ cm² was found. These local deposition concentrations can be tentatively extrapolated to the whole TEXTOR first wall. Using the surface area of the ALT-II and the inner DED limiter (area of $3.4 + 11$ m²) this results in a total inventory of $1.7 \pm 0.5 \times 10^{21}$ ¹⁸O-atoms stored in plasma-wetted surfaces. For storage in remote areas, by taking the obtained areal ¹⁸O densities on the metal (Al) surface as the lower and the retention in the shadowed carbon samples as the upper limit, a broad inventory range between 6.7×10^{20} and 1.1×10^{22} ¹⁸O-atoms is estimated. It is noted that this estimation suffers from poor knowledge of the effective remote area (open liner area: 24–38 m²), its surface composition and the plasma wall flux homogeneity. All values in the above surface analysis were corrected for the natural ¹⁸O isotopic content. Changes in ¹⁶O content were not detectable due to high background values in the exposed samples. With the measured neutral gas oxygen isotope ratio of 60% ¹⁸O (figure 2(b)) a total amount of $2.8 \pm 1.3 \times 10^{21}$ O-atoms is estimated to be stored in the main PFCs and $1.1 \times 10^{21}\text{--}1.8 \times 10^{22}$ O-atoms in remote areas.

The surface analysis estimation for the amount of oxygen to be found on the plasma-wetted surfaces shows agreement with the amount of oxygen recovered by D₂-ICWC obtained from mass spectrometry. The remaining oxygen retention as

Figure 3. Recovery of TEXTOR operation after O₂-conditioning using multi-pulse D₂-ICWC and He-ICWC. Top to bottom: density, density control signal, total gas consumption and radiated power of ohmic discharges before O₂/He-ICWC (blue), and before (green, NSB) and after the recovery conditioning procedure consisting of 1h47 of D₂-ICWC and 23 min of He-ICWC (red). The chronology of the experiment is shown in figure 1.

determined from mass spectrometry is in the obtained range for storage in remote areas estimated by surface analysis. Both these findings support the assumption of predominant oxygen recovery from surfaces with plasma contact. The estimated range by surface analysis for the total oxygen retention after O₂/He-ICWC operation has large uncertainties due to scatter in the measured areal oxygen densities, but covers the value obtained by mass spectrometry: $3.9 \times 10^{21}\text{--}2.1 \times 10^{22}$ versus $(1.7 \pm 0.5) \times 10^{22}$. Further detailed surface analysis is presented in [14]. Co-deposit removal from castellation gaps could not be assessed in this experiment. First results from TOMAS and KSTAR are however presented, respectively, in [15, 16].

4. Plasma restart after oxygen removal by ICWC

Figure 3 shows the density and gas consumption of the ohmic discharge ($I_p = 400$ kA, $n_e = 2 \times 10^{19}$ m⁻², $B_T = 1.9$ T) right before O₂/He-ICWC (blue), and those ran before (green) and after the recovery by D₂ and He-ICWC (red). The NSBs after O₂/He-ICWC were due to high electron cooling by O-impurities. The particle balance presented in the previous section concluded that after the recovery conditioning procedure still a significant amount of oxygen was stored in the vessel walls (540 mbar l). Nevertheless, a stable ohmic discharge has been established in the first attempt. As figure 3 illustrates, the density control via gas injection was very good during this ohmic discharge: the density followed the set value very well, the valve control signal had little oscillation

Figure 4. Characteristic oxygen radiation time traces of ohmic discharges before O₂-conditioning and after the recovery procedure by ICWC. A small but systematic increase in the oxygen radiation level can be seen. Top: horizontal viewing line looking at the ICRH antenna A2 (O II at 442 nm), bottom: vertical viewing line looking at the ALT-II limiter (O I at 777.5 nm).

and the high gas consumption evidenced low recycling fluxes from the wall. For a similar ohmic power level, the radiated power fraction was even slightly lower after recovery (figure 3, bottom).

Characteristic oxygen radiation time traces measured along two viewing lines are plotted in figure 4. The horizontal chord (top figure) looking at the ICRH antenna A2 showed no increased oxygen radiation during the discharge. The ICRF antennas were not operated during the ohmic discharges and the detected radiation values were close to the noise level. At the end of the controlled current ramp-down however the plasma visibly (CCD camera images) interacted with the antenna structure resulting in the measured oxygen radiation peak. The peak was twice as high for the first discharge after the recovery (#118311) compared with the ohmic discharge right before the O₂/He-ICWC experiment (#118748). Even though the height of such peaks is sensitive to the specific discharge termination, this difference is most likely related to the remaining oxygen in the vessel. The difference was clearer for the characteristic oxygen line recorded by a vertical chord (bottom figure) looking at the toroidal belt limiter (ALT-II). The integral of the signal over the current flat top phase gives an overall oxygen radiation increase by a limited factor of 1.5 in the first recovered discharge (#118311), decreasing to 1.3 in the second (#118312), giving further evidence for oxygen storage in remote areas.

5. Discussion and implications for ITER

The remaining oxygen retention after the recovery conditioning procedure did not prevent ohmic breakdown. This suggests that ICWC has sufficiently conditioned the wall surfaces that are in close contact with the ohmic plasma in the different

phases of the discharge, while the remaining oxygen is stored in more remote areas. The surfaces in contact with the plasma are the poloidal limiters, the toroidal ALT-II limiter and the inner DED target limiter. It is known that the plasma density in ICWC plasmas decreases exponentially close to the vessel walls where the magnetic field lines are limited by wall structures [10]. Consequent to the existence of this edge plasma, the ion wall flux will be largest on the first limiting surfaces, being the same surfaces in contact with the plasma during tokamak discharges on TEXTOR. While the areas receiving the conditioning flux are cleaned efficiently, the shadowed areas likely feature net retention of discharge gas during the conditioning procedure. In such a case the RF duty cycle may be adapted so that little wall-desorbed particles are re-deposited [11]. Unlike on present devices, on ITER the ion wall flux is expected to be more homogeneous since no dedicated poloidal limiting structures other than the shaped first wall itself will be present in the vessel [12]. Consequently, the ICWC plasma edge, as it exists on present devices, will not exist on ITER making the storage in remote areas less important.

The feasibility of wall conditioning with oxygen for tritium removal hinges upon the amount of tritiated products (e.g. water) produced in the process. Assuming a typical hydrogen isotope concentration of 0.4 H-isotopes/C-atom in tokamak carbon co-deposits [13] and a fusion fuel isotopic ratio of 50% (T/(D + T)) the estimated 6.6×10^{21} carbon atoms removed as CO or CO₂ during O₂/He-ICWC (table 1) translate into a potential tritium removal from co-deposits of 1.3×10^{21} atoms or 6.6 mgT in the 39×4 s discharges. The actually pumped amount of H-isotopes as water (1.7×10^{21} atoms, table 1) and molecular hydrogen (4.2×10^{21} atoms), 5.4×10^{21} atoms in total, exceeds and may thus include the two times 1.3×10^{21} D and T isotopes stemming from co-deposits. The direct comparison between these two quantities is however more complicated as characteristic times for e.g. desorption, ionization, dissociation and pumping are different for the considered molecules. Pumping of methane or heavier hydrocarbon molecules is not included in this analysis as it is considered only small in these O-abundant plasmas. The carbon and simulated tritium removal rate on TEXTOR is evaluated accounting for sufficient time between pulses to pump the relevant wall-desorbed molecules, approximately three characteristic pumping times. With an optimal RF duty cycle of 4 s/60 s for CO, CO₂ and water removal, this results in 0.2 gC h^{-1} and 10 mgT h^{-1} on TEXTOR. A tentative extrapolation for the achievable T-removal from co-deposits in 39×4 s pulses on ITER, taking into account the TEXTOR (C: $3.4 + 11 \text{ m}^2$, liner: max. 38 m^2) and ITER (Be: 700 m^2 , W: 100 m^2 [13]) wall surface areas, delivers promising results although at this point the dependence on the surface material is neglected. An extrapolation from TEXTOR C-area to ITER W-area supposes that the gross of the deposits are located in the divertor area, resulting in a removal of 46 mgT, which can be considered as a lower estimate. Extrapolating from total TEXTOR C + liner-area to total ITER W + Be-area gives 100 mgT. This value corresponds to a removal rate of 0.16 gTh^{-1} . An upper value, extrapolating from TEXTOR C-area to ITER W + Be-area, assumes additional tritium storage on the ITER beryllium first wall. This shaped surface, belonging to the ICWC plasma-wetted area, ensures

access to the storage areas resulting in a possible removal of up to 370 mgT. All three estimates are close to or in the range of the estimated retention per 400 s DT-burn (140–500 mgT [1]).

The prospect of using oxygen discharge conditioning is not certain for the nuclear phase of ITER. The oxygen discharges imply production of large quantities of tritiated water (DTO), which may feature enhanced production of extremely corrosive peroxides and is possibly beyond what the ITER Tokamak Exhaust Processing plant can handle. Moreover, the use of large quantities of oxygen in the exhaust gas is excluded for safety reasons [1].

Regardless of the applicability of O₂-ICWC on ITER, the value of the presented experiment lies largely in the successful tokamak operation recovery by D₂ and He-ICWC. The ITER vacuum vessel can be (oxygen, etc) contaminated from uncontrolled sources (e.g. leaks, replacement materials, accidental events, etc). ICWC may be envisaged for recovering machine operation after such events. Demonstrating the operational effectiveness of ICWC is naturally required for consolidating the technique prior to its application on ITER. Earlier successful demonstrations are the recovery by He-ICWC after disruptions on Tore Supra [17] and the promising inter-pulse conditioning results on KSTAR [18], where He-ICWC was used in order to keep the vessel H₂O pressure below the operational limit.

6. Conclusion

ICWC will be used on ITER during operational phases, i.e. in the presence of the toroidal magnetic field, for reducing the generation of plasma impurities, controlling the recycling of hydrogenic fluxes and for mitigating the tritium inventory build-up by removing tritium-rich co-deposited layers. The presented TEXTOR experiment is considered a self-consistent demonstration covering all of the above wall conditioning aims. O₂/He-ICWC was applied to erode carbon co-deposits, removing 6.6×10^{21} C-atoms (39 pulses, 158 s cumulated discharge time). The large oxygen retention however, namely 71% of the injected oxygen, prevented subsequent ohmic discharge initiation. A 1h47 multi-pulse D₂-ICWC procedure effectively cleaned the main plasma-facing components from oxygen impurities whereafter 23 min of multi-pulse He-ICWC was applied to desaturate the deuterium-loaded walls. The successful tokamak operation recovery could be demonstrated by establishing stable ohmic discharges on the first attempt right after the recovery procedure. The discharges showed improved density control compared with the reference discharges. The oxygen characteristic radiation had only slightly increased (1–1.5 times) with respect to the discharges before O₂/He-ICWC even though the oxygen balance by mass spectrometry suggested that after the recovery still 36% of injected O-atoms were retained in the vessel. This amount is in the estimated range for storage in remote areas obtained from surface analysis of locally exposed samples. The removed amount of oxygen

by D₂ and He-ICWC corresponds to the retention in plasma-wetted areas estimated by surface analysis. Based on these results it is concluded that due to ion transport along toroidal magnetic field lines, the first field line intersecting components receive the highest conditioning flux and are cleaned efficiently. Shadowed areas, e.g. behind poloidal limiters, may feature net retention of the discharge gas. On ITER, designed with a shaped first wall, the ICWC plasma-wetted area will approach the total surface area, reducing consequently the total retention in remote areas. A tentative extrapolation of the carbon removal on TEXTOR to tritium removal from co-deposits on ITER in the 39×4 s O₂/He-ICWC discharges, including pumping time between the RF pulses to remove wall-desorbed gases, corresponds on ITER to a tritium removal in the order of the estimated retention per 400 s DT-burn (140–500 mgT).

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