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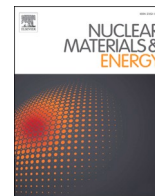
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Changeover between helium and hydrogen fueled plasmas in JET and WEST

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ABSTRACT

The pre-fusion power operation (PFPO) phase of ITER, as described in the ITER research plan with Staged Approach,² includes both hydrogen (H) and helium (He) plasma operations. In preparation for PFPO, both WEST and JET ran He plasma campaigns to study plasma-wall interactions in a tungsten environment. The campaigns included a back-and-forth transition between H or deuterium (D) and He plasma operation allowing the assessment of the achievable plasma content as well as the accessible wall reservoirs for respective species. The WEST changeovers included tokamak pulses with a fixed divertor configuration. The JET changeovers applied ion cyclotron wall conditioning (ICWC) and tokamak pulses including limiter phases and four different divertor configurations. Glow discharge conditioning (GDC) was applied to complete the changeovers. The results are characterized by subdivertor optical and mass spectrometric gas analyzers and spatially resolved optical emission spectroscopy. A He content of 96–97 % after H operations is achieved by tens of ICWC pulses (JET) and several dedicated diverted plasmas (WEST and JET), while a fivefold is estimated to be required for the back transition. Effective pumping of the wall released species is a key parameter for a fast changeover. Upon applying higher heating power, the relative content of the fueled plasma species decreases. The JET gas balance analysis indicates that He operation may increase H retention. WEST divertor spectroscopy indicates a larger He inventory near the inner divertor strike line. He GDC has a clear effect on the He recycling light at the WEST divertor while D GDC did not reduce the long lasting He content observed in D pulses after the JET He campaign.

¹ See the author list of J. Mailloux et al 2022 Nucl. Fusion 62 042026 [DOI 10.1088/1741-4326/ac47b4].

² ITER Organization, "ITER Research Plan within the Staged Approach," ITR-18-003, Aug. 2018.

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1. Introduction

The pre-fusion power operation phase of the ITER research plan with Staged Approach [1], includes both hydrogen (H) and helium (He) plasma operation for achieving H-mode without nuclear activation of the vacuum vessel components. The performance of the tungsten (W) divertor may be affected by this phase. The intense He flux at the divertor leads to specific structural changes [2,3], impacting fuel recycling properties [4] and degradation of its thermal properties [5]. WEST (C4 campaign [6]) and JET (C43 campaign [7,8]) ran helium plasma operations to study plasma-wall interactions in a tungsten environment. Both campaigns included a changeover between hydrogen or deuterium (D) and helium plasma operation allowing the assessment of the achievable plasma content as well as the accessible wall reservoirs for these species. These two experiments are described in this paper. Section 2 introduces the WEST changeover conditions, neutral gas analysis results and poloidally resolved spectroscopy along the inner and outer lower divertor. Section 3 presents complementary results from JET with additional gas balance analysis and results on the long-term evolution of the residual helium content in deuterium discharges up to 5 operation days after the helium campaign.

2. Changeover in WEST

2.1. Experiment overview

At the end of the C4 experimental campaign in D in WEST with all W PFC, a changeover from D to He plasma operation was conducted by operating repetitive plasmas in a single null configuration ($I_p = 500$ kA, $n_i = 3-4 \times 10^{19} \text{ m}^{-2}$) on the inertially-cooled lower divertor, either in ohmic or in L-mode using lower hybrid heating ($P_{LH} = 3$ MW). The changeover was diagnosed by poloidally resolved visible spectroscopy. Langmuir probes and infrared surface temperature measurements are available to study the dependence of the recycling flux on the ion fluence and surface temperature. Outgassing after each discharge was monitored by optical gas analysis (OGA, penning gauge spectroscopy). Threshold ionization mass spectrometry (TIMS) [9] data is available to obtain a global particle balance for each pulse. A 4 h He-glow discharge cleaning (GDC) was operated overnight twice to complete the changeover.

Fig. 1 shows the D₂ (blue dots) and He (red dots) content in the neutral gas after each discharge over three experimental days, comprising three changeovers between D and He operation. The content is deduced from partial pressure measurements in the divertor using OGA, integrated from the start of the discharge until 25 s post-discharge. The vertical dashed lines indicate the overnight He-GDC. Although

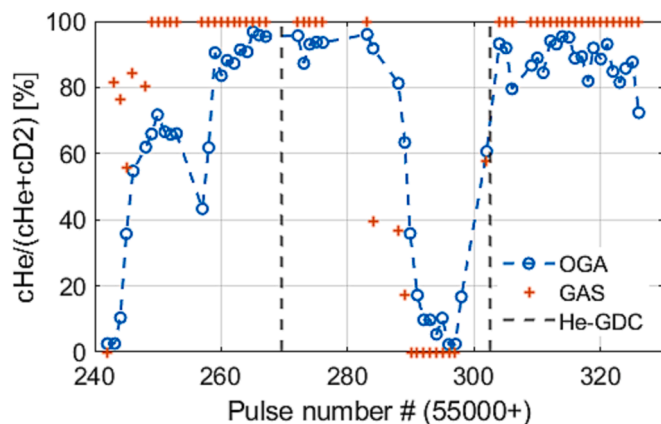


Fig. 1. D₂ and He content in released gas after discharges assessed from sub-divertor OGA in WEST. Pulse numbers without data points had a non-sustained breakdown or aborted sequence by the plasma control system.

plasma breakdown could be achieved in He, it was attempted in D in the first 10 pulses of the first D to He changeover, after which pure He fueled the discharge. This resulted in a high residual D content in the neutral gas of minimum 30 %. In the next pulses, with pure fueling throughout, either He or D₂, a plasma purity of 90–95 % is achieved within 10 discharges, corresponding to 50 s of cumulated discharge time. Towards the end of the experiment, at a higher Lower Hybrid heating power of up to 3 MW, the D content in He pulses increases to ~10–20 %. As the neutral pressure is very low at the divertor baffles during discharges, the changeover is mainly driven by wall pumping during the discharges and partial release of gas after the pulse. The active pumping system has a marginal effect on the plasma density and hence plasma composition.

TIMS analysis described in [10] highlighted several differences in outgassing behavior for the He and D species during the post-discharge. First, D outgasses for a 10 times longer duration than He after a discharge. Second, the maximum outgassing pressure of D after a pulse can be delayed by tens of seconds compared to the He maximum, in discharges that did not disrupt. The latter behavior was seen for both ohmic and lower hybrid heated pulses. The effect is observed also in the JET experiments described in section 3, and explained for WEST [10] by a slow temperature equilibration of the inertially-cooled divertor surface followed by thermal desorption from locations that are heated in the post discharge phase.

2.2. Poloidally resolved spectroscopy

A comparison of the recycling fluxes of D and He is obtained through absolutely calibrated visible spectroscopy measurements using multiple lines of sight (LOS) intercepting the lower divertor [11,12]. Fig. 2 shows the relative intensity of He recycling compared to the total recycling flux (estimated from He I and D- γ characteristic lines) along the divertor target in poloidal direction, as a measure of the plasma content. The outer strike point corresponds to viewing line 17–18; the lower LOS numbers are closer to the high field side. The line ratios are averaged over a 1 s time interval at the end of each discharge and plotted as a function of the cumulated discharge time. Only the two first changeovers are considered. The He content in the recycling flux of He-fueled plasmas varies fastest at the outer strike line. Further away on the outer divertor and at the inner divertor, about 25 s more are needed for achieving a similar line ratio. The He-GDC completes the changeover away from the strike line. In the back transition, more time is needed to decrease the He content near the outer strike lines than elsewhere, indicating a larger He inventory at this location. Finally, at the outer strike line, a higher residual content of He in D pulses is found (15 %) compared to D in He pulses (3 %).

3. Changeover in JET

3.1. Experiment overview

The JET C43 campaign commenced with a back-and-forth transition between He and H plasma operation performed using ion cyclotron (IC) wall conditioning (ICWC) followed by limiter and IC heated (<2 MW) diverted plasmas. The ICWC and limiter phases were mainly intended to remove fuel from the beryllium main chamber surfaces. The diverted plasmas used different configurations within a pulse to ensure maximum wetting and removal from the W divertor surfaces. The ICWC discharges were 16 s long, with a coupled RF power of 0.16 MW and 0.24 MW in the H and He discharge, respectively [13]. Detailed analysis of the ICWC conditions are available in [13]. The diverted plasmas included the JET standard Tile 5 configuration (V5), the ITER-like vertical target configuration (VT), a corner-corner configuration (CC) and the raised inner strike point (RISP) configuration developed for fuel removal from beryllium co-deposits on the upper tiles of inner divertor [14]. The divertor configurations, and their performance for T removal, are detailed in [15]. Two pulse types were applied for the H and He plasmas,

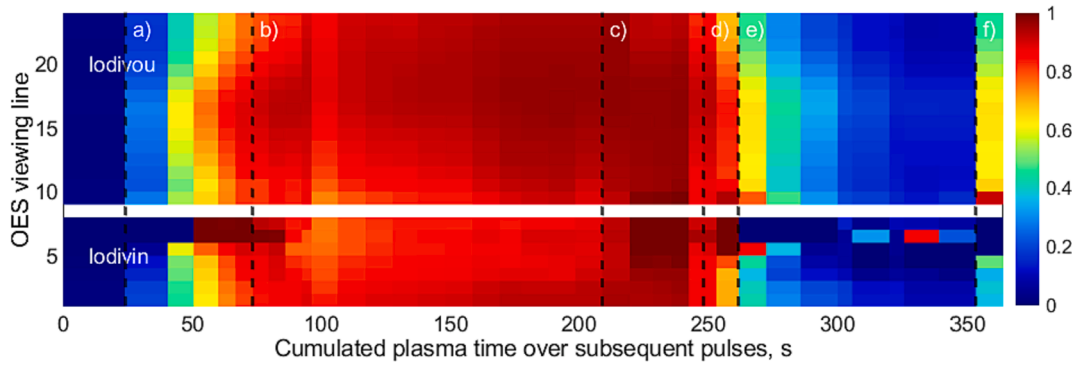


Fig. 2. Analysis of the recycling flux by poloidally resolved spectroscopy at the WEST lower inner and outer divertor (“lodivin” and “lodivou”, respectively). Plotted is the ratio of He recycling light (He I 388.9 nm) to total emission (He I, D- γ 434.1 nm and H- γ), time averaged over 1 s, 1 s before the end of the discharge, as a function of the total cumulated discharge time: a) Start D to He changeover, b) He injection only, c) 4 h He-GDC, d) Start He to D changeover, e) D₂ injection only, and f) He reference pulse. The lower viewing line numbers are closer to the high field side, the outer strike point corresponds to viewing line 17–18. The analysis data is calibrated to units of Photons m⁻² s⁻¹ sr⁻¹.

one with a 5 s limiter phase followed by 16 s in V5, CC and VT phase, and one with 16 s in RISP configuration where the outer strike line is displaced from the horizontal Tile 6 to the vertical Tile 7 after 5 s to partition the energy load on the tiles.

Chronologically, in 5 subsequent sessions preceded by He operations, the experiment applied 15H ICWC pulses, 6H plasmas, 8 He ICWC pulses, 9 He ICWC pulses with cryopumping and 4 He plasmas with cryopumping. It is to be noted that, even in the case of cryopumping, the JET cryopanel does not pump He, nor molecular H (H₂) efficiently below the vapor pressure of $\sim 10^{-5}$ mbar in JET. Argon-frost cryopumping, a method to trap He and H₂ on the cryopanel, was not applied throughout the changeovers. Reference pulses in either H or He are performed before and after each H and He session, respectively. These included a limiter phase followed by a V5 diverted phase. At the start of the experiment, before the first reference pulse in H, a He reference was taken to allow comparing the initial H content in He fueled plasmas to that obtained after completion of the back-and-forth transition. The experiment is diagnosed by the sub-divertor optical gas analysis (OGA) system [16], providing concentrations of H, D and He in the exhaust gas, and residual gas analyzers (RGA, mass spectrometry) [17], sensitive to lower partial pressures. The RGAs are calibrated by controlled gas injection sequences without plasma. Optical emission spectroscopy (OES) systems, with LOS in the main chamber and in the divertor [18] are used to estimate the plasma composition.

3.2. Optical gas analysis and spectroscopy

Fig. 3 summarizes the plasma composition evolution by OES and OGA for the both fueling changeovers in JET. The OES data points taken from the horizontal midplane LOS compare H- γ and D- γ to He I emission intensities. Both depend sensitively on the plasma parameters, electron density and temperature, which are unknown. Thus the He and H plasma content and its evolution throughout the experiment is traced only qualitatively by OES. As plasma parameters change between ICWC, limiter and the different divertor configurations, the ranges of obtained line intensities are rescaled separately for each plasma type between zero and the maximum emission intensity observed throughout the pulses. The obtained intensity ratio corresponds closely to the concentration ratio in the sub-divertor neutral gas, indicated by black stars (OGA in the figure legend). The reference plasma pulses are plotted in purple (Ref in the figure legend), ICWC discharges in red, plasma discharges in green, with each symbol indicating a different discharge phase or configuration as indicated in the figure legend. Yellow-filled symbols are pulses with He fueling, blue-filled ones are in H.

The experiment started with 3.6 % H and ended with 3.7 % H, as measured by OGA in the diverted phase of He reference pulses. The maximum hydrogen concentration obtained is 97.3 % in the diverted phase of the last H reference pulse, although generally in the diverted plasmas the He content is higher in H plasmas (~ 0.15) than the H

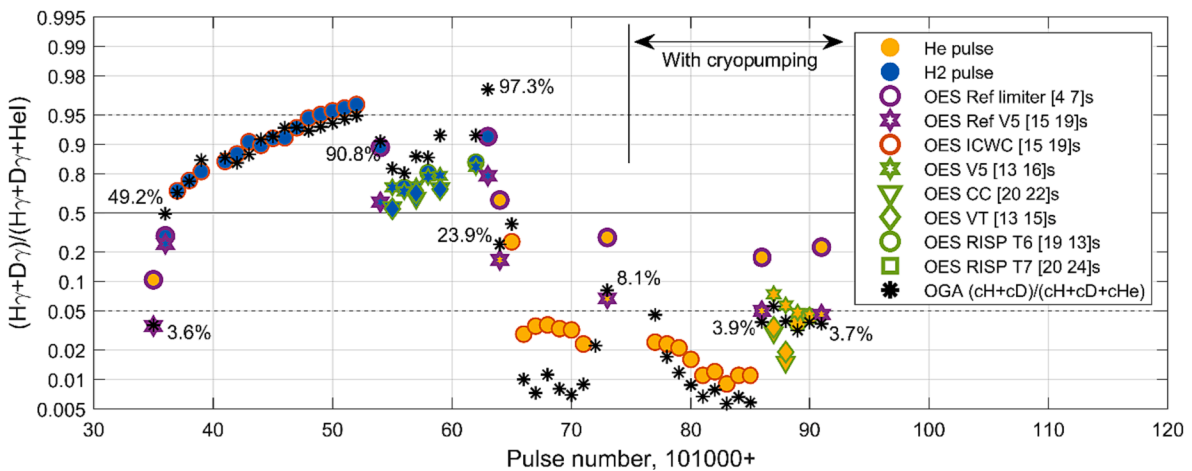


Fig. 3. Plasma content in subsequent changeover pulses in JET by KS3 horizontal OES viewing line (estimation from 434.1 nm H- γ and D- γ vs. 447.15 nm He I) and sub-divertor OGA (black stars), separated by discharge phase and He or H fueling (yellow vs. blue marker face color). Note the logarithmic scale of the y-axis, starting from a concentration of 50 %, to both the higher and lower concentrations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

content in He (~ 0.04). The latter is also true in ICWC discharges. The limiter phase of the reference plasmas have generally a higher H content compared to diverted plasmas based on OES, although this may result from the described method of rescaling the emission intensities. OGA did not allow verifying this observation. At low divertor pressures in the limiter phase, the OGA is not sufficiently sensitive to measure the gas content. The measurements shown are taken in the diverted phase. The H ICWC pulses show a gradual increase of the hydrogen content to 95 % in 15 pulses, increasing the H content in the reference discharges from 49.2 % to 90.8 %. Note that the same cumulated discharge time can be applied in 30 min on a superconducting device such as ITER at a pulse duty cycle of 12.5 %. The lower H content in the 6 subsequent diverted H pulses results from their stronger plasma interaction with the divertor, where He is trapped in W at a higher rate than on the Be main chamber surfaces, as well as from the different wall fueling vs. valve fueling rates in ICWC vs. tokamak plasmas.

The back transition by He pulses started with a lower H content of 23.9 %H in the first He reference pulse, compared to 49.2 % of He in the first H reference pulse, reduced to 8.1 %H by 8 He-ICWC pulses. The second series of ICWC discharges, operated with cold cryopanel, saw a stronger reduction of the hydrogen content. In the subsequent reference and diverted pulses, the H content stagnates at about 3.8 %.

Unlike in WEST, there was no clear sign of different changeover rates in the spatially resolved divertor OES lines in JET. This results possibly from changing the divertor configurations within and in subsequent pulses, effectively conditioning a large part of the divertor at the same rate. In He pulses, the OES LOS observing the strike line position had consistently a lower H concentration compared to other locations, possibly resulting from lower H recycling at the strike lines, or different plasma parameters favoring the He I emission to H- γ .

3.3. Gas balance by mass spectrometry

The content of the neutral gas is analyzed by the sub-divertor mass spectrometry to quantify the removed and retained amounts of H and He in the two changeovers. The integral of the removed H_2 and He, obtained using RGA signals for mass to charge ratios 2 and 4 respectively, is plotted in Fig. 4 together with the injected gas amounts. Deuterium is not analyzed, its content being less than 10 % of H in the H pulses, resulting in HD formation mostly with less than 1 % of D_2 , and too low to be quantified in the He pulses. The last ICWC and plasma pulses in He with cryopumping are not analyzed either due to too low H content.

The gas balance of H pulses shows similar H retention per pulse (right plot in Fig. 4, injected minus outgassed) as compared to He removal per pulse (left plot), while He pulses have higher He retention (left plot) than H removal. Integrated, a similar amount of He is retained in the H to He

back transition to that previously removed in the He to H transition, 1.20 bar.l vs. 1.14 bar.l, possibly a mere coincidence. On the other hand, more H is retained in the integral as compared to the amount removed by He plasmas, afterwards, 3.49 bar.l vs. 0.73 bar.l. Note that this analysis ignores outgassing beyond 250 s after the pulse. As reported for WEST [10], JET He plasmas also featured a strongly delayed H outgassing peak by tens of seconds compared to the He outgassing. The H removal is however similar to that reported in full W ASDEX Upgrade when scaled for vessel surface area [19]. Unlike in ASDEX Upgrade, the He-ICWC pulses removed similar amounts of H_2 compared to the He-reference plasmas, 0.17 bar.l vs 0.20 bar.l, possibly due to a lower number of analyzed ICWC pulses (7 in JET vs 19 in ASDEX Upgrade) and a lower applied RF power relative to the plasma volume (300–400 kW in JET vs 100–200 kW in ASDEX Upgrade).

3.4. Long term residual He content after He campaign

The He content in the neutral gas was continuously monitored by sub-divertor OGA after the JET He campaign. It shows a noticeable and only slightly decaying He content in D_2 pulses of 3 to 4 % during one operations week, as shown in Fig. 5. The content is shown as function of pulse number after the last He discharge, and sampled only for discharge phases with more than 5 MW of input power. The different symbol colors

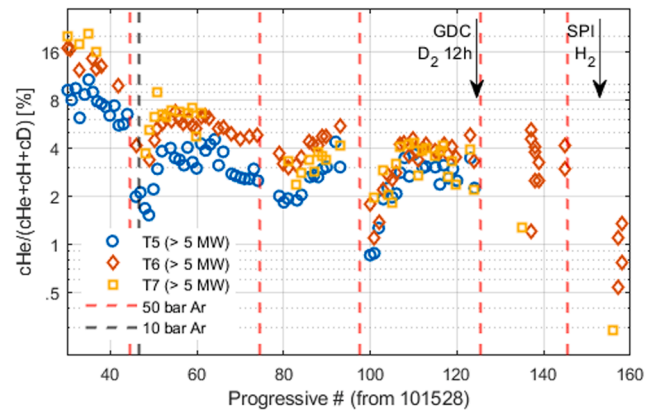


Fig. 5. He content compared to H and D content from sub-divertor OGA in D_2 plasmas following the JET C43 He campaign. The markers sample different diverted phases with more than 5 MW of input power. Application of argon (Ar) -frost cryopumping is indicated by vertical dashed lines. A 12 h long D_2 glow discharge is applied where indicated by the back arrow. The last plotted day operated discharges terminated by injection of shattered H pellets (SPI).

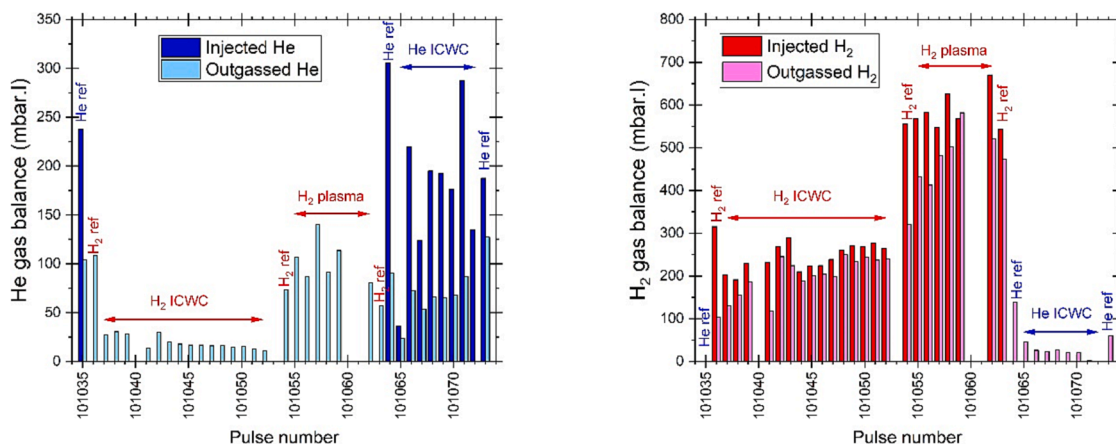


Fig. 4. Pulse-based gas balance analysis of JET changeover experiment from sub-divertor RGA using calibrated mass 2 and mass 4 intensities for H_2 and He respectively. Integration includes the discharge and 250 s post discharge time.

separate discharge phases according to the location of the outer strike line, either on Tile 5, 6 or 7. The application of Argon-frost on the cryosurfaces, indicated by dashed vertical lines, reduces the helium content due to effective He pumping. This indicates that the high residual He content, while indicating persistent He retention in the PFCs, is largely due to inefficient evacuation of He. Note that cryopanel with active charcoal, such as in ITER [20], can pump He nearly as efficiently as D and H, leading to a lower lasting He content. After the 4th D₂ operations day, a 12 h glow in D₂ is performed without much effect on the helium content. Disruptions with shattered hydrogen pellets on the last plotted day decrease the He content to below 1 % in diverted phases with more than 5 MW of input power.

4. Summary

WEST (the C4 campaign) and JET (the C43 campaign) ran He plasma operations to study plasma-wall interactions in a W environment, complementing the results obtained earlier in ASDEX Upgrade [19]. JET operates with a W divertor and beryllium main chamber wall while WEST has all W PFC. Both campaigns included changeovers between H (D) and He plasma operation allowing the assessment of the achievable plasma content as well as the accessible wall reservoirs for these species. Due to a low pumping efficiency of both He and H(D) by active pumping in both experiments, the changeover is mainly driven by wall pumping during the discharges and the partial release of gas after the pulse.

From OGA, a quasi-steady plasma purity is achieved within 50 s of cumulated discharge time in WEST corresponding to about 10 discharges, and within tens of ICWC pulses followed by 50 to 100 s of tokamak plasmas in JET. Both in WEST and in JET, the quasi-steady plasma composition has a higher residual content of He in H(D) pulses (10–15 %) compared to H(D) in He pulses (3–4 %). The plasma purity is lower at higher plasma heating. A lasting residual He content of 3–4 % in D pulses is observed up to 5 operation days after the JET He campaign, which results partially from the inefficient pumping of He compared to D₂ in JET in absence of argon frosting on the cryosurfaces. A 12 h long D₂ GDC did not reduce the high lasting He content.

In the D to He transition in WEST, OES shows a faster changeover at the outer divertor strike line compared to other LOS, while the opposite is observed in the back transition from He to D. This indicates that the He inventory builds up mostly at the strike lines while H(D) retention occurs more uniformly over the W divertor surface. A 4 h He GDC completed the H to He transition away from the strike line in WEST.

The gas balance analysis in JET showed a 4.7 times higher H retention in the He to H transition, compared to removal in the back transition (0.73 bar.l). The H removal is similar to that reported in full W ASDEX Upgrade when scaled for vessel surface area [19], with a lower contribution from ICWC possibly due to a lower number of ICWC pulses and a lower applied RF power relative to the plasma volume. He removal in the H to He transition in JET, as well as the retention in the back transition are of the order of 1 bar.l.

The present experiments suggest that He and H plasma operation in ITER PFPO needs to consider distinct characteristic times for achieving relatively pure (96–97 %) plasmas. One ICWC sequence with sufficient coupled power and several diverted plasmas are sufficient in the H to He transition, while a fivefold may be needed in the back transition, based on the observed lasting He content after the He campaign. Effective pumping of the wall released species is a key parameter for a fast changeover, which translates in an adapted pulse duty cycle in case of ICWC and sufficient neutral compression in diverted changeover pulses. Upon applying higher heating power, the relative content of the fueled plasma species decreases. Finally, although not conclusive, the JET gas balance analysis indicates that He operation increases H retention; the changeover from He to H retained more H than the removed amount measured in the He plasmas of the back transition. This effect may be most pronounced at the high heat flux areas such as the divertor (W) strike line, where a slower changeover rate observed by WEST divertor

spectroscopy in the He to H transition indicates a larger He inventory. The transition from helium to hydrogen results in retaining more hydrogen than the quantity removed by helium plasmas in subsequent phases.

CRedit authorship contribution statement

T. Wauters: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **R. Bisson:** Formal analysis. **E. Delabie:** Supervision. **D. Douai:** Formal analysis. **A. Gallo:** Supervision. **J. Gaspar:** Formal analysis. **I. Jepu:** Formal analysis. **Y. Kovtun:** Formal analysis. **E. Pawelec:** Supervision. **D. Matveev:** Formal analysis. **A. Meigs:** Supervision. **S. Brezinsek:** Formal analysis. **I. Coffey:** Formal analysis. **T. Dittmar:** Formal analysis. **N. Fedorczak:** Formal analysis. **J. Gunn:** Formal analysis. **A. Hakola:** Supervision. **P. Jacquet:** Supervision. **K. Kirov:** Formal analysis. **E. Lerche:** Supervision. **J. Likonon:** Formal analysis. **E. Litherland-Smith:** Supervision. **T. Loarer:** Formal analysis. **P. Lomas:** Supervision. **C. Lowry:** Formal analysis. **M. Maslov:** Formal analysis. **I. Monakhov:** Formal analysis. **J. Morales:** Formal analysis. **C. Noble:** Formal analysis. **R. Nouailletas:** Formal analysis. **B. Pégourié:** Formal analysis. **C. Perez von Thun:** Formal analysis. **R.A. Pitts:** Supervision. **C. Reux:** Formal analysis. **F. Rimini:** Formal analysis. **H. Sheikh:** Formal analysis. **S. Silburn:** Formal analysis. **H. Sun:** Formal analysis. **D. Taylor:** Formal analysis. **E. Tsitrone:** Supervision. **S. Vartanian:** Formal analysis. **E. Wang:** Supervision. **A. Widdowson:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- [1] ITER Organization, "ITER Research Plan within the Staged Approach," ITR-18-003, Aug. 2018. Accessed: Aug. 20, 2019. [Online]. Available: https://www.iter.org/doc/www/content/com/Lists/ITER%20Technical%20Reports/Attachments/9/ITER-Research-Plan_final_ITR_FINAL-Cover_High-Res.pdf.
- [2] Y. Ueda, et al., Research status and issues of tungsten plasma facing materials for ITER and beyond, *Fusion Eng. Des.* 89 (7–8) (2014) 901–906, <https://doi.org/10.1016/j.fusengdes.2014.02.078>.
- [3] G. De Temmerman, R.P. Doerner, R.A. Pitts, A growth/annealing equilibrium model for helium-induced nanostructure with application to ITER, *Nucl. Mater. Energy* 19 (2019) 255–261, <https://doi.org/10.1016/j.nme.2019.01.034>.
- [4] M. Ialovega, et al., Hydrogen trapping in tungsten: impact of helium irradiation and thermal cycling, *Phys. Scr.* 2020 (T171) (2020) 014066, <https://doi.org/10.1088/1402-4896/ab68bd>.

- [5] L. Buzi, et al., Response of tungsten surfaces to helium and hydrogen plasma exposure under ITER relevant steady state and repetitive transient conditions, *Nucl. Fusion* 57 (12) (2017) 126009, <https://doi.org/10.1088/1741-4326/aa81e4>.
- [6] E. Tsitrone, et al., Investigation of plasma wall interactions between tungsten plasma facing components and helium plasmas in the WEST tokamak, *Nucl. Fusion* 62 (7) (2022) 076028, <https://doi.org/10.1088/1741-4326/ac2ef3>.
- [7] M. Maslov, et al., "ELMy H-mode Helium plasma at JET-ILW," in Europhysics conference abstracts, Bordeaux, France: Europhysics Conference Abstracts, 2023, p. O4.108. [Online]. Available: http://fusionwiki.ciemat.es/fusionwiki/index.php/European_Physical_Society_Conference_on_Plasma_Physics.
- [8] A. Hakola, "29th Fusion Energy Conference (FEC 2023)," in: IAEA Conference Contributions, London, UK: IAEA, 2023. Accessed: Aug. 20, 2023. [Online]. Available: <https://conferences.iaea.org/event/316/contributions/27811/>.
- [9] C.C. Klepper, et al., Extending helium partial pressure measurement technology to JET DTE2 and ITER, *Rev. Sci. Instrum.* 87 (11) (2016) 11D442, <https://doi.org/10.1063/1.4963713>.
- [10] R. Bisson, et al., Deuterium and helium outgassing following plasma discharges in WEST: Delayed D outgassing during D-to-He changeover experiments studied with threshold ionization mass spectrometry, *Nucl. Mater. Energy* 26 (2021) 100885, <https://doi.org/10.1016/j.nme.2020.100885>.
- [11] O. Meyer, et al., Development of visible spectroscopy diagnostics for W sources assessment in WEST, *Rev. Sci. Instrum.* 87 (11) (2016) 11E309, <https://doi.org/10.1063/1.4959780>.
- [12] A. Grosjean, et al., Refining light impurity content estimates at the lower divertor based on experimental data in WEST, *Nucl. Mater. Energy* 35 (2023) 101385, <https://doi.org/10.1016/j.nme.2023.101385>.
- [13] Y. Kovtun, "Comparison of Ion Cyclotron Wall Conditioning Discharges in Hydrogen and Helium in JET," *Nucl. Mater. Energy*, vol. 19th International Conference on Plasma-Facing Materials and Components for Fusion Applications, 22 to 26 May, 2023, Bonn, Germany. ID: 123, no. In review, 2023.
- [14] T. Wauters, et al., Isotope removal experiment in JET-ILW in view of T-removal after the 2nd DT campaign at JET, *Phys. Scr.* 97 (4) (2022) 044001, <https://doi.org/10.1088/1402-4896/ac5856>.
- [15] D. Matveev, et al., Tritium removal from JET-ILW after T and D-T experimental campaigns, *Nucl. Fusion* 63 (11) (2023) 112014, <https://doi.org/10.1088/1741-4326/acf0d4>.
- [16] S. Vartanian, et al., Simultaneous H/D/T and 3He/4He absolute concentration measurements with an optical Penning gauge on JET, *Fusion Eng. Des.* 170 (2021) 112511, <https://doi.org/10.1016/j.fusengdes.2021.112511>.
- [17] U. Kruezi, et al., Neutral gas analysis for JET DT operation, *J. Instrum.* 15 (01) (2020) C01032, <https://doi.org/10.1088/1748-0221/15/01/C01032>.
- [18] V.S. Neverov, A.B. Kukushkin, U. Kruezi, M.F. Stamp, H. Wiesen, Determination of isotope ratio in the divertor of JET-ILW by high-resolution H α spectroscopy: H-D experiment and implications for D-T experiment, *Nucl. Fusion* 59 (4) (2019) 4, <https://doi.org/10.1088/1741-4326/ab0000>.
- [19] A. Hakola, et al., Plasma-wall interaction studies in the full-W ASDEX upgrade during helium plasma discharges, *Nucl. Fusion* 57 (6) (2017) 6, <https://doi.org/10.1088/1741-4326/aa69c4>.
- [20] C. Day, D. Murdoch, R. Pearce, The vacuum systems of ITER, *Vacuum* 83 (4) (2008) 773–778, <https://doi.org/10.1016/j.vacuum.2008.05.010>.