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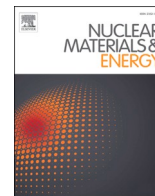
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Wall conditions in WEST during operations with a new ITER grade, actively cooled divertor

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ABSTRACT

Future fusion reactors like ITER and DEMO will have all-tungsten (W) walls and long pulses. These features will make wall conditioning more difficult than in most of the existing devices. The W Environment Steady-state Tokamak (WEST) is one of the few long pulse (364 s) fusion devices with actively cooled W plasma-facing components in the world. WEST is a unique test bed to study impurity migration and plasma density control via reactor relevant wall conditioning techniques. The phase II of WEST operations began in 2022, after the installation of a new lower divertor, now entirely equipped with actively cooled, ITER grade, W monoblocks. After pump down, we baked WEST between 90 °C and 170 °C for ~2 weeks. After 82.5 h at 90 °C and 33 h at 170 °C, vacuum conditions were stable with a vessel pressure of 6×10^{-5} Pa and mass spectra dominated by H₂ molecules. While at 170 °C, we performed ~40 h of D₂ glow discharge cleaning (GDC) and ~5 h of glow discharge boronization (GDB), using a 15 %-85 % B₂D₆-He mix and a total boron mass of ~12 g. This was the very first GDB at such high temperature for WEST. The whole wall conditioning sequence led to a ~10 times reduction of the H₂O signal as well as to a ~3 times reduction of the O₂ signal, according to mass spectra. Once back to 70 °C, the vessel pressure was 5.5×10^{-6} Pa and plasma restart was seamless with ~30 s cumulated over the very first 5 pulses and an Ohmic radiated power fraction $F_{\text{rad}} = 0.6$, showing successful conditioning of the new ITER grade divertor. The effect of the first, ‘hot’ GDB faded with a characteristic cumulative injected energy of 2.45 GJ and saturation towards $F_{\text{rad}} \sim 0.8$. After 1.4 h and 7.5 GJ of cumulative plasma time and injected energy, we carried out a second GDB, this time at 70 °C. This ‘cold’ GDB initially led to a much lower Ohmic $F_{\text{rad}} = 0.3\text{--}0.4$ but the effect lasted ~7 times less, with a characteristic cumulative injected energy of 0.37 GJ. At the end of the campaign, we cumulated ~3h and ~30 GJ through repetitive, minute long pulses without any boronization. Throughout this 4-weeks-long experiment, F_{rad} in the 4 MW heating phase evolved only marginally (from 0.5 to 0.55). This increase is mostly due to the build-up of re/co-deposited layers on both lower divertor targets.

Issues specific to wall conditioning in tungsten, long pulse tokamaks

Next-generation fusion devices like ITER and DEMO will sport all-tungsten (W) walls and perform plasma pulses as long as minutes [1,2]. These features will pose new challenges in terms of plasma-wall interactions and will make wall conditioning more difficult than in current experiments. We rely mainly on Glow Discharge Cleaning (GDC)

for the removal of tungsten oxide (W_xO_y) layers formed during a vent, as well as co-deposited layers formed during plasma operations, and on Glow Discharge Boronization (GDB) for the deposition of nanometric boron (B) layers which help with reducing the partial pressure of oxygen (O). However, glow discharges require the absence of a magnetic field: the magnet technology envisioned for ITER will not allow an indefinitely high number of ramp up/down cycles hence ruling out glow discharges as a possible routine solution. The large vacuum vessel surface will

¹ <http://west.cea.fr/WESTteam>.

² See the author list of Progress on an exhaust solution for a reactor using EUROfusion multimachines capabilities by E. Joffrin et al. to be published in Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16-21 October 2023).

require higher injected quantities of diborane (B_2D_6) gas and possibly longer GDB durations in order to deposit B layers of the same thickness of existing devices (about 10 nm in several hours). Moreover, higher particle and energy flux at Plasma-Facing Components (PFC) and especially long plasma pulses (e.g. 1000 s) will lead to much faster B migration. Instead, in existing, short pulse devices a GDB every couple of weeks (e.g. 10 s/pulse * 15 pulses/day * 4 days/week = 600 s/week) is enough to maintain acceptable wall conditions in terms of impurity content and radiation as well as in density control. Therefore, it is crucial to study and optimize wall conditioning techniques in experiments that couple W PFC with long plasma pulses. In Europe, we have one such experiment.

Phase II of WEST operations: New ITER grade, actively cooled divertor

The W Environment Steady-state Tokamak (WEST) [3,4] is one of the few pulse fusion devices with actively cooled W PFC in the world. With a designed plasma duration of 1000 s (364 s achieved so far), WEST is a unique test bed to study impurity migration and plasma density control via reactor relevant wall conditioning techniques. Between 2015 and 2021, during phase I, WEST operated with a W-coated, inertial, carbon (C) lower divertor. Phase II of WEST operations began in 2022, after the installation of a new lower divertor, now entirely equipped with actively cooled, ITER grade, W monoblocks [5]. The main mission of WEST is indeed to qualify this technology, representative of the vertical targets in the ITER divertor design (Fig. 1), under a peak heat flux density of 10 MW m^{-2} in steady state (6 MW m^{-2} achieved so far) [6].

In Fig. 2 we present a typical WEST pulse from the 2022–2023 experimental campaign, the one discussed in this work, with: plasma duration of several tens of seconds, plasma current $I_p = 400 \text{ kA}$ (purple), injected Lower Hybrid Current Drive (LHCD) power $P_{LHCD} = 4 \text{ MW}$ (blue), central line-averaged density $n_l = 4 \times 10^{19} \text{ m}^{-2}$ (green), radiated power $P_{rad} = 2.2 \text{ MW}$ (red) corresponding to a radiated power fraction $F_{rad} = 0.55$, and deuterium (D_2) gas throughput as high as $2 \text{ Pa m}^3 \text{ s}^{-1}$ at the onset and then stabilizing at $0.2 \text{ Pa m}^3 \text{ s}^{-1}$ after about 15 s.

ITER-relevant wall conditioning techniques in WEST

The way we historically carry out wall conditioning in WEST prior and during an experimental campaign is via three main, state-of-the-art techniques: bake, GDC, and GDB. Since 2020, WEST is also equipped with an Impurity Powder Dropper (IPD) provided by PPPL and discussed in separate, dedicated publications [7,8,9,10]. We bake WEST utilizing

the main water-cooling loop up to a maximum temperature of $200 \text{ }^\circ\text{C}$. It takes about two days to reach maximum bake temperature from room temperature. After vent and pump down but before the bake, we usually obtain a vessel pressure of several $1 \times 10^{-5} \text{ Pa}$ while Residual Gas Analyzers (RGA) installed onto the midplane, main pumping duct indicate that particles with $m/Z=18$, mainly water (H_2O) molecules, dominate the vacuum. We typically bake WEST for as long as needed for the $m/Z=18$ signal to become smaller than the $m/Z=2$ signal, indicating that the vacuum is dominated by hydrogen (H_2) molecules instead. This usually takes between 2 and 4 days of bake. Since at the time of writing we have not calibrated the midplane RGA, in the following, we will refer to I_X as the ion current measured by the RGA for particles with $m/Z=X$. Once $I_2/I_{18} > 5$, we proceed to perform 1–2 days of D_2 GDC. The glow discharge system in WEST consists of six electrodes located in the top part of the vacuum vessel and equally spaced in the toroidal direction (Fig. 3a). New glow electrodes, installed in 2020, have a circular design and are made of low cobalt stainless steel with an aluminum nitride, insulating ring (Fig. 3b). They can take up to 900 V and 2.5 A. The same electrodes are utilized for GDB in a gas mixture of He (>85 %) and B_2D_6 (<15 %) from six dedicated injection locations in the bottom part of the vacuum vessel near the low field side wall (Fig. 3c). A typical GDB in WEST lasts about 5 h, which roughly correspond to a 10 bar consumption of the He/ B_2D_6 gas bottle (8 L) and to 10–12 g of injected B. We can carry out GDC and GDB at both bake temperature and at plasma operation temperature ($70 \text{ }^\circ\text{C}$) depending on the need for other concomitant activities that we cannot undertake while at bake temperature due to safety constraints. During both GDC and GDB, we isolate all divertor pumps, and we pump the vessel solely via the midplane main pumping duct.

Ion Cyclotron Wall Conditioning (ICWC) in WEST is currently being developed through dedicated experiments but not available yet. Other than that, WEST already sports the same wall conditioning techniques foreseen in ITER and it is, therefore, in prime position to contribute to the preparation of such aspect of ITER operations.

Preparation of the 2022–2023 WEST experimental campaign

The first experimental campaign of WEST phase II, after the installation of the new ITER grade, actively cooled lower divertor, took place between December 2022 and April 2023. Elsewhere we might refer to this campaign as C6 and C7 for the 2022 and 2023 portions, respectively. This campaign represented an opportunity to assess whether the standard WEST conditioning sequence is adequate to (re)start operations after the installation of an entirely new divertor composed of 15960 W monoblocks of the technology adopted by ITER [11]. In

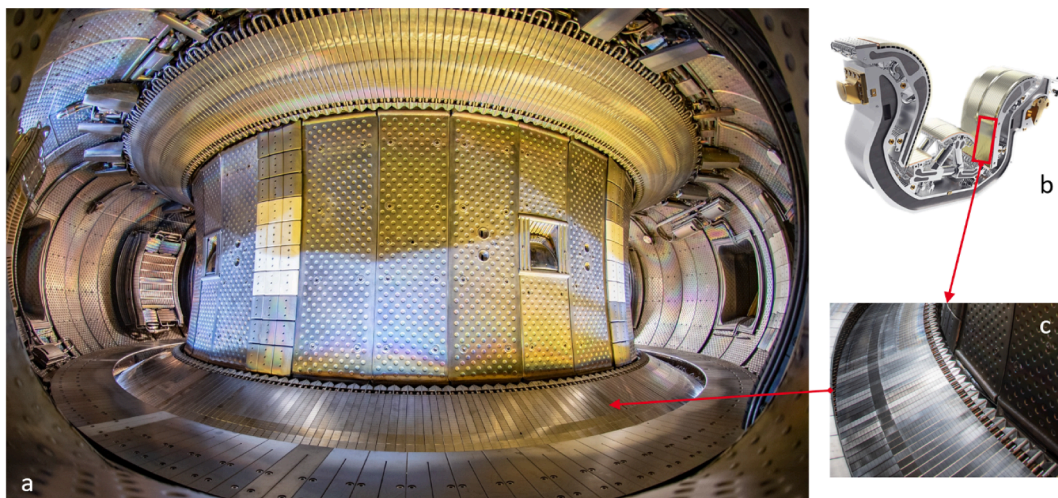


Fig. 1. A) Inside of the WEST vacuum vessel, b) ITER divertor cassette, c) ITER grade divertor in WEST.

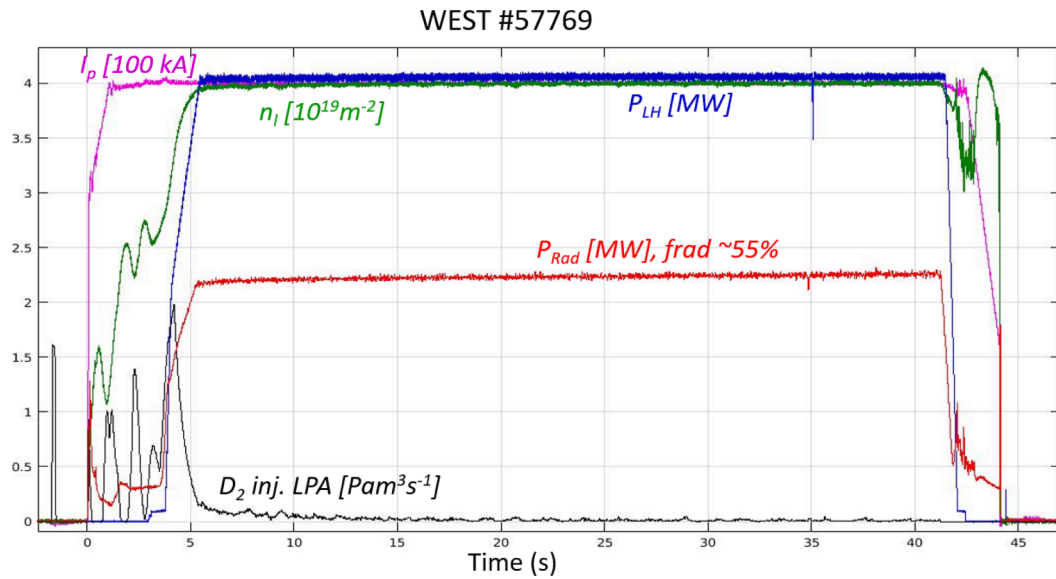
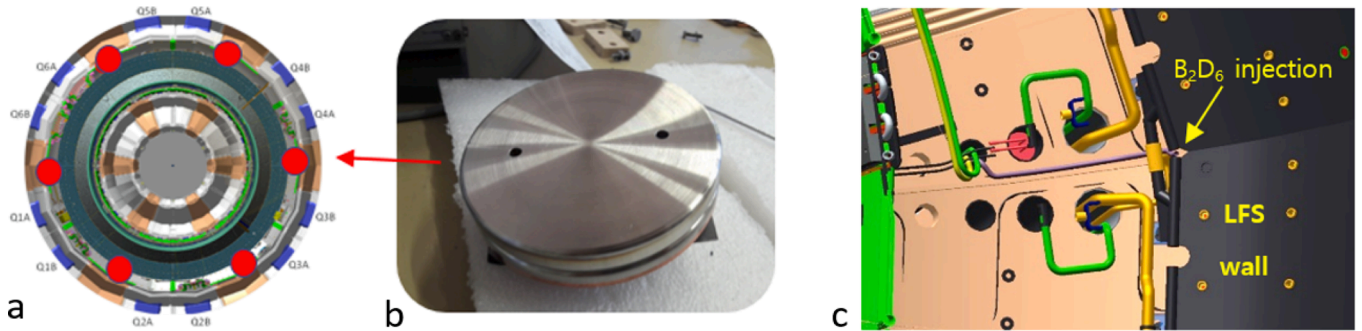


Fig. 2. Typical WEST phase II pulse with plasma current (magenta), injected power (blue), central line-averaged density (green), radiated power (red), and D_2 gas throughput (black).



November 2022, after pump down, we baked WEST between 90 °C and 170 °C for about 2 weeks. After a total of 82.5 h at 90 °C and 33 h at 170 °C, vacuum conditions were stable with a vessel pressure of 6×10^{-5} Pa

and mass spectra dominated by H_2 molecules (Fig. 4, first yellow shaded area). Since the $I_2/I_{18} > 5$ condition was met, while at 170 °C, we performed a total of ~40 h of D_2 GDC (Fig. 4, purple shaded areas),

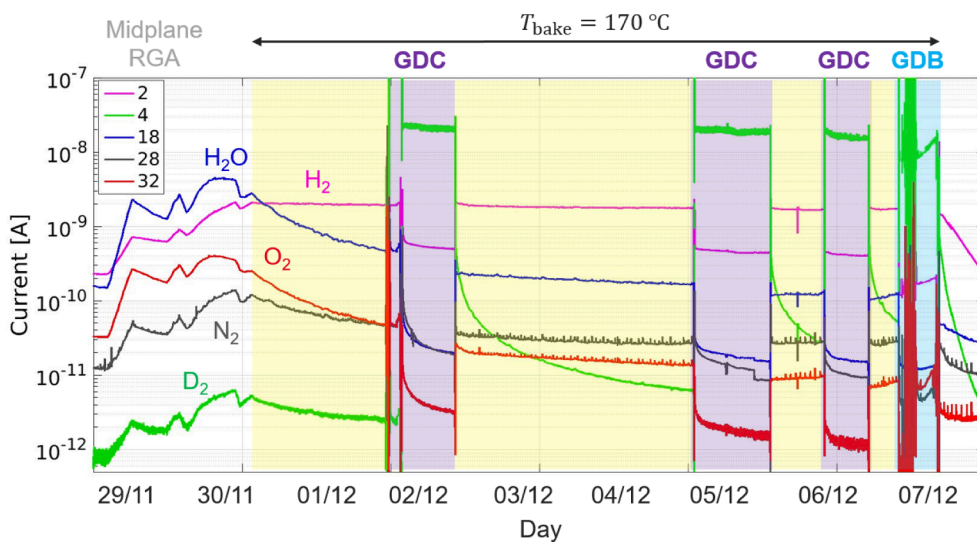


Fig. 4. Midplane RGA currents during the wall conditioning sequence prior to the 2022–2023 WEST campaign. Mass to charge ratios in the legend are complemented by the most likely associated species above each curve: 2 (H_2), 4 (D_2), 18 (H_2O), 28 (N_2), 32 (O_2).

followed by ~ 5 h of GDB (Fig. 4, cyan shaded area). This was the very first GDB at such high temperature in the history of WEST. The whole wall conditioning sequence led to a ~ 10 times reduction of I_{18} (Fig. 4, blue line) as well as to a ~ 3 times reduction of the O_2 signal I_{32} (Fig. 4, red line) according to mass spectra. Once back to plasma operation temperature (70°C) we measured a vacuum vessel pressure of 6×10^{-6} Pa. This was a record-low value for WEST but it might be due to also the repair of several micro air leaks during the 2022 shutdown and not solely to good wall conditions or to the presence of the new, pristine lower divertor.

Evolution of wall conditions during the 2022–2023 WEST experimental campaign

After carrying out the wall conditioning sequence described above, we successfully resumed plasma operations in WEST. The restart was seamless with ~ 30 s of cumulated plasma time (t_{cum}) over the very first 5 pulses. As usual at the beginning of each new WEST experimental campaign, we continued the wall conditioning via a series of Ohmic plasma pulses in both inboard-limited and lower-diverted configuration. In Fig. 5a and 5b respectively, we display in blue dots F_{rad} and the effective charge Z_{eff} during the first 150 Ohmic plateaus of the 2022–2023 campaign. With plateau, we refer to any portion of a plasma pulse with steady I_p and n_1 that lasts at least 300 ms [12]. In these early plateaus, conditions proved to be good for WEST standards, as indicated by an average $F_{\text{rad}} = 0.55$ and an average $Z_{\text{eff}} = 1.32$. By comparison, we include the same data for the last two campaigns of WEST phase I. During the first 150 plateaus of the 2020–2021 campaign (red squares) we did measure an average $F_{\text{rad}} = 0.61$ and an average $Z_{\text{eff}} = 1.63$, respectively $\sim 10\%$ and $\sim 20\%$ higher than the 2022–2023 one. During the first 150 plateaus of the 2019 campaign (green diamond) we instead did measure a significantly higher average $F_{\text{rad}} = 0.78$ as well as a higher Z_{eff} (an average value is not provided as Z_{eff} measurements in the first ~ 50 plateaus were not reliable). One needs to consider, though, that in 2020 we replaced several W tiles of both the inboard limiters and the outboard, movable, limiter with boron nitride (BN) ones [13]. For this reason, 2019 data are not directly comparable and we display them only for reference. The comparison between 2022–2023 and 2020–2021 data, though, is a meaningful one as the only difference was the new, ITER grade lower divertor: this new component, made of pristine bulk W monoblocks with no damage, erosion or deposition zones prior to its installation, had a positive impact on early plasma operations once successfully conditioned.

In order to study the evolution of wall conditions throughout the entire 2022–2023 campaign, one can look at F_{rad} as a function of the cumulated injected energy E_{cum} , as in Fig. 6. Here the color bar

represents t_{cum} , while the solid vertical lines correspond to the two GDB carried out earlier on. In this analysis we restrict ourselves to Ohmic diverted plateaus only, in an attempt to rule out as much as possible the role of the different plasma scenarios (heating scheme and power, strike point position, impurity seeding, et cetera). As indicated by the green bracket in Fig. 6, we dedicated the first portion of the campaign ($t_{\text{cum}} \sim 2$ h, $E_{\text{cum}} \sim 12$ GJ) to performance experiments, namely plasma heating and core physics studies, which require freshly boronized walls to minimize impurity content and radiation loss. We instead devoted the second part of the campaign ($t_{\text{cum}} \sim 3$ h, $E_{\text{cum}} \sim 28$ GJ), indicated by the red bracket in Fig. 6, to the high particle fluence experiment: it consisted of repetitive ~ 1 min long pulses to cumulate the fluence of about two ITER pulses of the Pre-Fusion Plasma Operation (PFPO) phase (5×10^{26} D m^{-2}) [14]. The focus of this experiment were plasma-wall interactions taking place at the surface of the ITER grade, W monoblocks at fixed plasma scenario. We hence avoided any GDB to reduce the impact of B layers on the results.

By separately analyzing the two portions of the campaign, we can better understand the role of GDB (or the lack thereof) on the evolution of wall conditions. Fig. 7 corresponds to a zoom of the left portion of Fig. 6, and is therefore representative of Ohmic, lower diverted plateaus during performance experiments. Here the red vertical line indicates the first GDB, carried out at the end of the 170°C bake and prior to any plasma operation. In the very first plasma pulses, which allow pursuing the wall conditioning via the outgassing of light impurities from limiter and divertor tiles, we measure $F_{\text{rad}} \sim 0.6$. This value evolves as a function of E_{cum} following an exponential trend that can be parametrized as $F_{\text{rad}} = A - B \exp(-E_{\text{cum}}/E_{\text{fade}})$. Here E_{fade} represents the cumulated energy at which the effect of GDB fades. After $E_{\text{cum}} = 7.5$ GJ and $t_{\text{cum}} = 1.4$ h, F_{rad} saturates at ~ 0.8 , which is a typical value for WEST Ohmic pulses far away from GDB. By fitting the data for these pulses after the ‘hot’ GDB we get $E_{\text{fade}} = 2.45$ GJ. In order to reduce again radiative losses, we then carried out a ‘cold’ GDB, indicated by the black vertical line in Fig. 7. Due to operational time constraints, it is in fact unusual to go back to bake temperature while boronizing but this gives us the opportunity to compare the effects of GDB at bake temperature with GDB at operation temperature. Right after this ‘cold’ GDB, we measured F_{rad} as low as $0.3\text{--}0.4$: this value is not directly comparable with the one right after the ‘hot’ GDB, as in this case substantial plasma conditioning had occurred before re-boronizing. Therefore, one cannot straightforwardly conclude that a ‘cold’ GDB necessarily provides a lower initial F_{rad} compared to a ‘hot’ one in WEST. The most striking difference, though, is $E_{\text{fade}} = 0.37$ GJ for the ‘cold’ GDB. This value is ~ 6.6 times smaller than for the ‘hot’ GDB and might indicate that the B-rich, co-deposited layers formed during the ‘cold’ GDB have either a smaller thickness or a different morphology that facilitates their erosion.

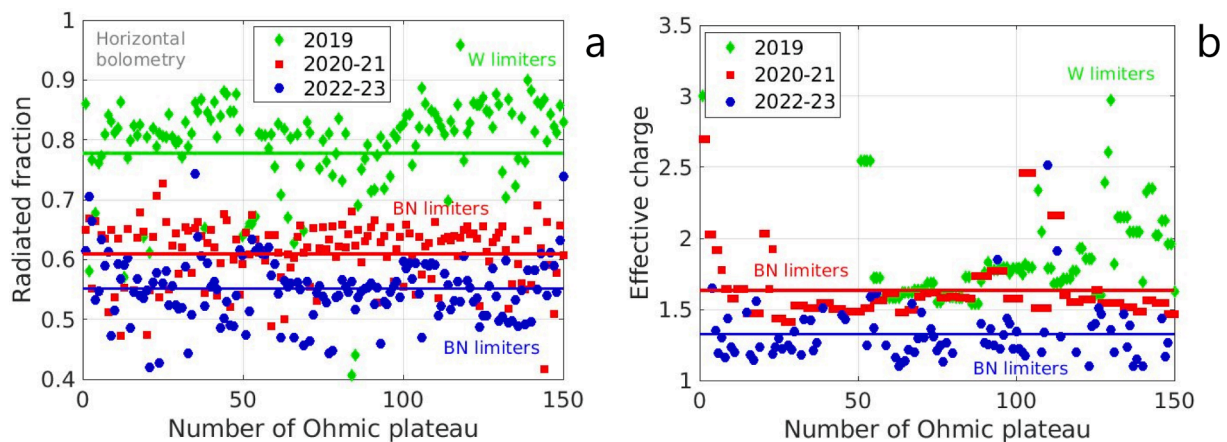


Fig. 5. a) radiated power fraction and b) effective charge during the first 150 ohmic plateaus of the 2019 (green diamonds), 2020–2021 (red squares) and 2022–2023 (blue dots) WEST campaign.

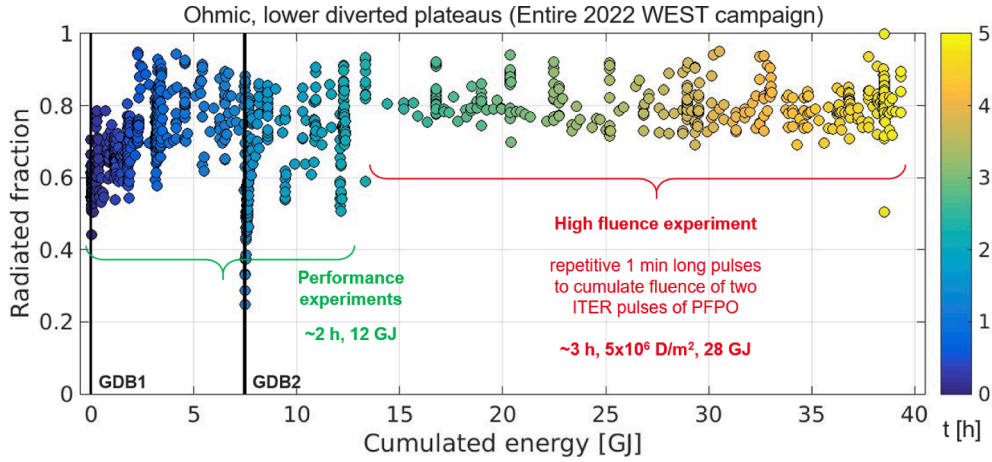


Fig. 6. Radiated power fraction as a function of cumulated injected energy during every Ohmic, lower diverted plateau of the 2022–2023 WEST experimental campaign. The color bar indicates the cumulated plasma time, vertical black lines indicate glow discharge boronizations.

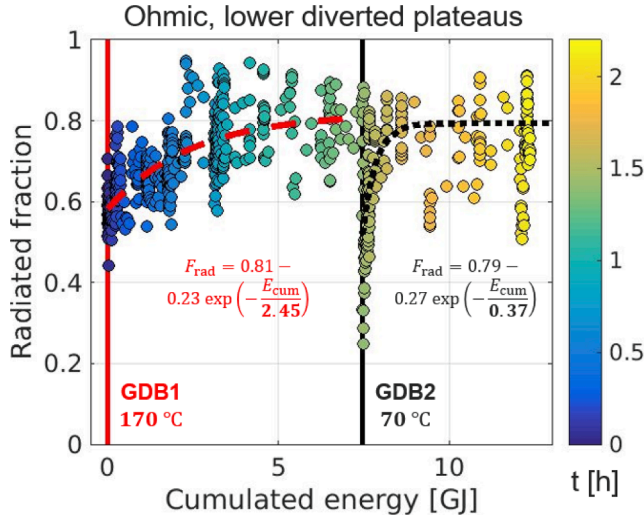


Fig. 7. Radiated power fraction as a function of cumulated injected energy during WEST performance experiments.

If one assumes a purely thermal cracking of B_2D_6 molecules and neglects the effect of the glow discharges, one can parametrize the B deposition rate γ as a function of the wall temperature T_w via the Arrhenius equation $\gamma \exp(-E_a/k_B T_w)$ where E_a is the molar activation energy (22 kcal/mol for B_2D_6) and k_B is the Boltzmann constant [15]. Under these assumptions a 100 °C increase in T_w would lead to a 3 orders of magnitude increase in γ . The difference in thickness of the B layers deposited during ‘hot’ and ‘cold’ GDB in WEST is most probably less dramatic but T_w could indeed play a role. We need further comparison, as well as results from post mortem analyses [16], to draw any conclusion.

Fig. 8 corresponds to a zoom of the right portion of Fig. 6, and is representative of lower-diverted plateaus during the high particle fluence experiment. Here we plot both Ohmic (black circles) and LHCD-heated (red squares) plateaus. Since this experiment consisted in repetitive ~ 1 min long pulses at fixed plasma scenario, a difference in F_{rad} during the heating phase is a trustworthy indicator of the evolution of wall conditions throughout the 4 weeks needed to reach $t_{cum} = 3$ h, $E_{cum} = 28$ GJ and a PFPO fluence at the outer divertor target of $5 \times 10^{26} \text{ D m}^{-2}$. Since the high particle fluence experiment started 4.5 GJ of plasma after the last GDB, we assume that any effect of GDB had meanwhile vanished. For the Ohmic plateaus, we measure an average $F_{rad} \sim 0.8$, a typical WEST value in non-boronized conditions, which stays constant

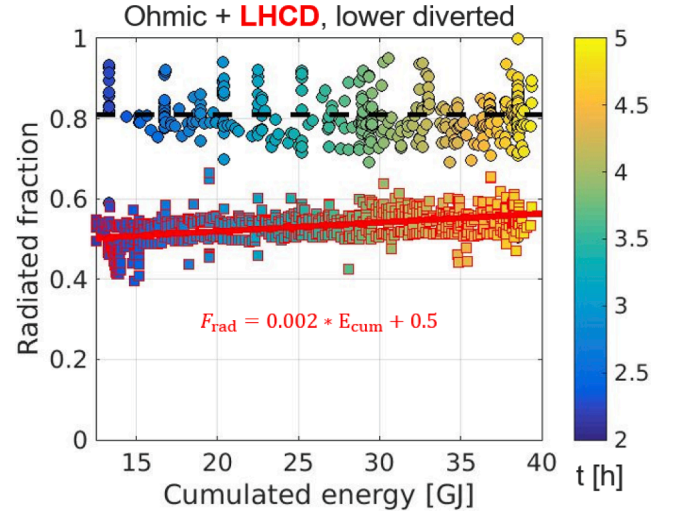


Fig. 8. Radiated power fraction as a function of cumulated injected during the WEST high particle fluence experiment.

throughout the experiment. During the 4 MW LHCD-heated plateaus, instead, we measure an initial average $F_{rad} \sim 0.5$ which linearly creeps up with E_{cum} and reaches ~ 0.55 by the end of the experiment. Such slow but steady increase of F_{rad} is mainly due to the bolometer lines of sight monitoring the lower divertor region. It is, therefore, most probably related to the remobilization of co-deposited layers composed by W migrated from the strike lines, a net erosion area, and light impurities like B, N, O and C inherently present in the machine [16].

The reason why we believe this is an interesting result is twofold. Firstly, we observe that the plasma scenario adopted for the high particle fluence experiment ($I_p = 400$ kA, $P_{LHCD} = 4$ MW, $n_l = 4 \times 10^{19} \text{ m}^{-2}$) proved to be reliable and reproducible even after what was an unprecedentedly high t_{cum} and E_{cum} for WEST. The only noticeable signs of degradation of wall conditions were the abovementioned 5% increase in F_{rad} and the steadily increasing frequency of UFOs taking off from the lower divertor co-deposits, sometimes entering the confined plasma and potentially causing a disruption [17]. Secondly, we note that any increase of F_{rad} with E_{cum} might anyway be problematic when extrapolating to ITER scales. Indeed the main ITER scenario will have to rely on a partially detached divertor regime to keep the steady state divertor heat flux density below 10 MW m^{-2} [11] that is also likely to mitigate material migration and, therefore, co-deposition. However, these results suggest that in a metallic machine wall conditions can degrade even at

moderate heating power and in L-mode when dealing with very high particle fluence and, more in general, with long pulse operations.

Conclusions and future experiments

We conclude that the wall conditioning sequence carried out at WEST before the beginning of the 2022–2023 campaign (bake at 170 °C with 40 h of D₂ GDC and 12 g of B injected during GDB while baking) proved to be compatible with the new, ITER grade, actively cooled lower divertor. Such sequence, followed by a second GDB earlier on in the campaign, allowed for successful long pulse operations for a total $t_{\text{cum}} = 5$ h and $E_{\text{cum}} = 40$ GJ in 4 months.

During the early portion of the campaign, freshly boronized walls helped mitigating radiative losses with Frad as low as ~ 0.4 during Ohmic, lower diverted plateaus, compared to the typical ~ 0.8 measured in WEST far away from GDB. The positive effect of the first ever ‘hot’ boronization in WEST on Frad lasted over a 6.6 higher E_{cum} when compared to a ‘cold’ GDB.

During the high particle fluence experiment, consisting of 4 weeks of repetitive, ~ 1 -minute-long pulses performed far away from GDB, we observed a 5 % increase of F_{rad} (from 0.5 to 0.55) mostly coming from the lower divertor region, where thick co-deposits built up. We need to address the role of B from GDB in the buildup of such co-deposits, and in the occurrence of UFOs that the co-deposits generate, to understand whether this could be a problem for ITER as well.

New experiments concerning the impact of GDB on fuel retention and the overall gas balance are ongoing at WEST as part of the 2023–2024 experimental campaign. This is the first time we carry out a dedicated set of identically programmed pulses before and after a GDB at WEST. This experiment, together with others with an impurity powder dropper [9,10], are essential to inform ITER about the transient as well as the long-term effects of boronization in a W machine on key aspects like vacuum conditions, mitigation of radiative losses, impurity migration, particle balance and fuel retention.

CRediT authorship contribution statement

A. Gallo: Writing – original draft, Investigation, Conceptualization. **Ph. Moreau:** Validation, Data curation. **D. Douai:** Validation, Data curation. **T. Alarcon:** Validation. **K. Afonin:** Validation. **V. Anzallo:** Validation. **R. Bisson:** Validation. **J. Bucalossi:** Validation. **E. Caprin:** Validation. **Y. Corre:** Validation. **M. De Combarieu:** Validation. **C. Desgranges:** Validation. **P. Devynck:** Validation. **A. Ekedahl:** Validation. **N. Fedorczak:** Validation. **J. Gaspar:** Validation. **A. Grosjean:** Validation. **C. Guillemaut:** Validation. **R. Guirlet:** Validation. **J.P. Gunn:** Validation. **J. Hillairet:** Validation. **T. Loarer:** Validation. **P. Maget:** Validation. **P. Manas:** Validation. **J. Morales:** Validation. **F.P.**

Pellissier: Validation. **E. Tsitrone:** Validation. **K. Krieger:** Validation. **A. Hakola:** Validation. **A. Widdowson:** Validation.

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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