

# Wall conditioning throughout the first carbon divertor campaign on Wendelstein 7-X

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## ABSTRACT

Controlling the recycling of hydrogen and the release of impurities from the plasma facing components proved to be essential and challenging throughout the first divertor campaign on W7-X. This paper discusses the conditioning requirements throughout the first divertor campaign on Wendelstein 7-X. Baking at 150 °C and glow discharge conditioning (GDC) in H<sub>2</sub> is performed after the initial pump down of the vacuum vessel. Experimental programs in hydrogen are interlaced with He discharges to desaturate the wall from hydrogen, recover good recycling conditions and hence establish plasma density control. Optimized He ECRH wall conditioning procedures consisted of sequences of short discharges with fixed duty cycle. He-GDC remained however needed before each experimental day to fully offset the hydrogen inventory build-up. A significant increase in the divertor temperature is observed throughout an operational day, enhancing outgassing of CO and H<sub>2</sub>O. Preliminary recombination-diffusion modelling of hydrogen outgassing suggests enhanced diffusion to deeper surface layers with increasing wall temperature, which results in better wall pumping. This indicates that the experienced plasma performance degradation throughout an operational day results from increased impurity outgassing at higher wall temperature rather than hydrogen saturation of the wall.

## 1. Introduction

The first divertor campaign of Wendelstein 7-X (OP1.2a) addressed (i) the verification of the island divertor configuration and the symmetrization of the heat loads on the divertor targets, (ii) achieving density control and core fueling by pellets in preparation of high-density, high-power steady-state operation and (iii) characterization of the intrinsic impurities, their sources and their transport [1]. Essential in these studies are controlling the recycling of hydrogen and minimizing the release of impurities from the plasma facing components (PFC) that occurs through plasma surface interaction processes. Applying wall-conditioning procedures such as baking, glow discharge conditioning (GDC) and ECRH conditioning, all available in OP1.2a, allows to effectively alter the surface conditions of the PFC's. This contribution presents the results of baking and GDC, applied before the first divertor plasmas on W7-X, as well as the role of GDC and ECRH discharges in

maintaining high discharge performance throughout the OP1.2a campaign. Boronization and ICRF conditioning are envisaged to complete the set of conditioning tools in upcoming operation campaigns.

The PFC's in OP1.2a consist of 10 discrete divertor units (total fine graphite target surface area: 25 m<sup>2</sup>, fine graphite baffle: 33 m<sup>2</sup>, stainless steel panels of the poloidal closure: 10 m<sup>2</sup>, fine graphite toroidal closure: 3 m<sup>2</sup>, stainless steel panels protecting the pumping gap: 10 m<sup>2</sup>) and the first wall protection system with 50 m<sup>2</sup> of fine graphite tiles clamped to CuCrZr cooling structures and 70 m<sup>2</sup> of stainless steel panels [2,3]. W7-X foresees active PFC cooling in future operations campaigns. In OP1.2a surfaces were adiabatically cooled to room temperature. The ECRH system operates at  $f = 140$  GHz with secondharmonic absorption at  $B_0 = 2.5$  T [4]. The free volume of the plasma vessel is about 110 m<sup>3</sup> with a plasma volume of 30 m<sup>3</sup>. 30 turbo molecular pumps provide vacuum with an effective pumping speed in the vessel of about 40 m<sup>3</sup>/s for H<sub>2</sub> [5]. The experimental arrangement for GDC on W7X involves 10

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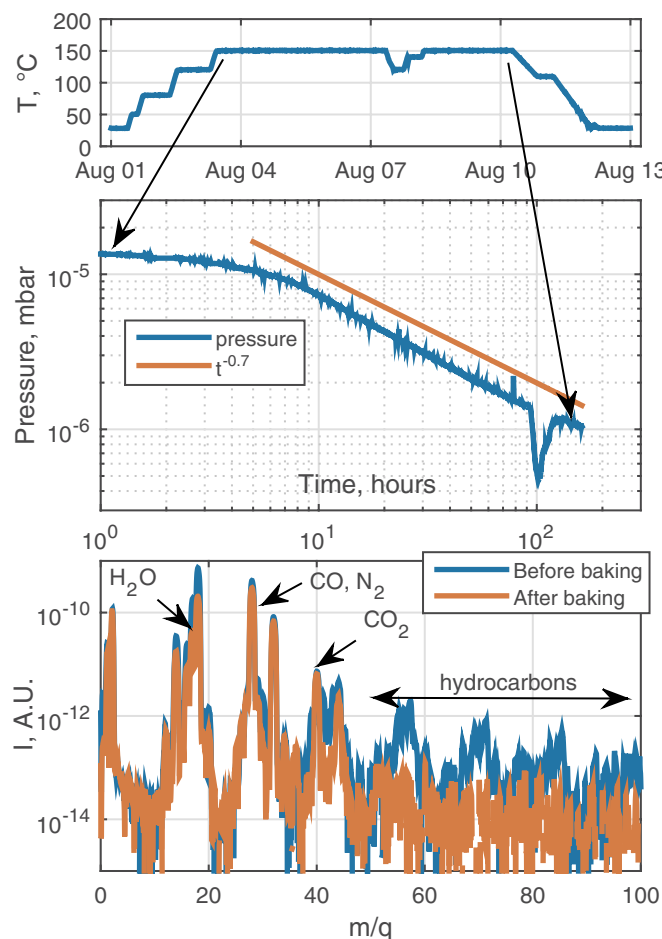


Fig. 1. Baking procedure preceding first plasma operation. Top: vessel temperature in time, including about 1 week at 150 °C. Middle: Pressure decay during 150 °C flat top phase and  $t^{-0.7}$  trend curve. Bottom: vacuum QMS spectra before (July 31) and after baking (August 12) at 28 °C.

graphite DC anodes, one per half module, operated at max. 1.5 A per anode [6]. GDC is operated between experimental days when the magnetic field coils are deenergized. H<sub>2</sub>-GDC and He-GDC are operated respectively weekly and daily.

## 2. Initial conditioning

### 2.1. Baking

One week of baking at 150 °C after the initial pump down of the vacuum vessel prepared the vessel for high vacuum. Heating of the wall materials induces thermal desorption of particles. Quadrupole mass spectrometry (QMS) shows that H<sub>2</sub>O is the main outgassed species, with about  $10^{25}$  H<sub>2</sub>O molecules removed throughout the procedure. CO and CO<sub>2</sub>, the next most prominent molecules, are released at  $> 10\times$  lower rates. A comparison of continuous QMS mass  $m$  over charge  $q$  spectra at 28 °C before (blue) and after (red) baking is given in Fig. 1. The footprint of higher hydrocarbons is suppressed while the water content is reduced by one order of magnitude. The pressure curve during the 150 °C temperature plateau follows a typical  $t^{-0.7}$  time dependency for outgassing in fusion devices [7] (Fig. 1b). The power law originates from processes such as de-trapping of particles at trapping site concentrations in the PFC, diffusion of those particles through the material bulk and their subsequent recombination to volatile molecules at the surface (Section 4.2). The dependency makes that the relative changes in the neutral pressure scale inversely proportional to time,  $1/p \, dp/dt \approx -t^{-1}$ , unlike for an exponential decay where latter quantity is

constant. With outgassing following a power law it becomes increasingly difficult in time to recover molecules from the vessel. Therefore, operating W7-X with hot walls, a technical capability of W7-X (150 °C), poses a challenge if no further conditioning methods are applied. Indeed, extrapolating the water pressure trend line to an arbitrary 100 baking days at 150 °C, the approximate duration of an operations campaign, reduces the water pressure to  $1.5 \times 10^{-7}$  mbar only. This is still approximately 10% of the H<sub>2</sub> or He filling pressure in W7-X ECRH discharges.

### 2.2. Hydrogen GDC

Hydrogen GDC, applied after the baking with PFC's at room temperature, further depletes the contamination layers on the wall surfaces. The produced energetic and nearly homogeneous flux of ions reduces metal oxides, hydrogenates the carbon surfaces and forms volatile species that can be evacuated from the vessel [8]. About  $10^{23}$ – $10^{24}$  molecules of CO are removed, estimated from QMS data. Fig. 2 shows QMS intensities for mass  $m$  over charge  $q$  signals corresponding to CH<sub>4</sub> ( $m/q = 16$ ), H<sub>2</sub>O (18), CO (28), Ar (40), and CO<sub>2</sub> (44) for subsequent H<sub>2</sub>-GDC's procedures as function of the cumulated GDC time. The signals are normalized to the applied glow current (1–1.5 A/anode). As chemical sputtering continuously generates CH<sub>4</sub> its signal saturates in time. The expected  $t^{-0.7}$  outgassing trend for other impurities is added as multiple black dashed lines. The stronger partial pressure decay in the first 50 s results from the step-by-step increase of the pumping speed to the maximum value and subsequent step-by-step decrease of the gas flow. The gas flow was doubled after this optimization procedure, which explains the observed partial pressure discontinuity at that time. The increased partial pressures at 650 s are consequent to an air leak that preceded the GDC, and that led to an increased torus pressure of  $5 \times 10^{-5}$  mbar within 5 h.

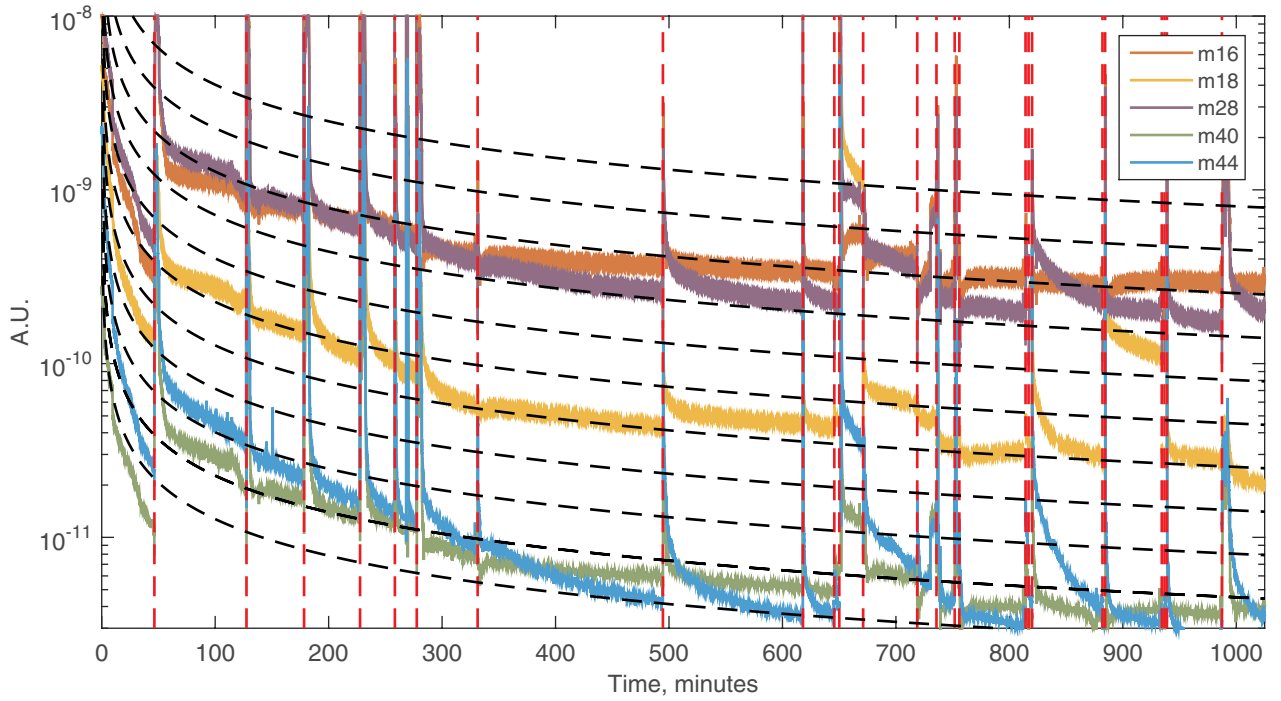
The vertical red dashed lines indicate ECRH operation days, with discharges in H<sub>2</sub> and He, which are typically preceded by 20–45 min of He-GDC. The first ECRH plasma operation took place after 50 min of H<sub>2</sub>-GDC. The last H<sub>2</sub>-GDC was performed before the last operations week of the campaign. The impurity partial pressures develop along a single envelope curve from H<sub>2</sub>-GDC to H<sub>2</sub>-GDC. ECRH operation as well as He-GDC clearly has little effect on the overall removal trend. This can be understood from a localized plasma surface interaction area in the diverted plasmas and the absence of chemical processes in He-GDC. The presence of impurities on the surfaces in the first operation days did not prevent operating W7-X close to the set energy limits. Nevertheless, impurity radiation in the plasma was high, density control in H<sub>2</sub> was challenging and radiative collapses occurred frequently.

## 3. Wall desaturation by Helium conditioning

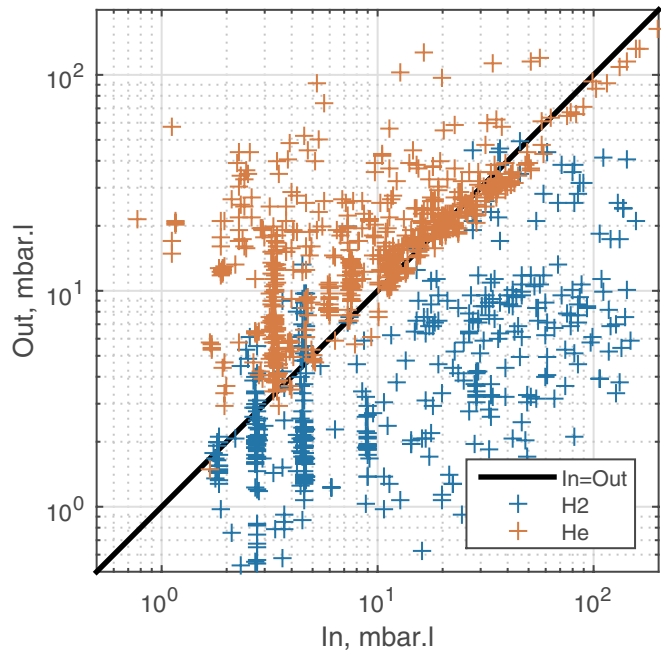
### 3.1. Gas balance

Fig. 3 plots the pumped amount of gas vs. the injected amount of gas for all experiments in OP1.2a. It clearly illustrates that generally H<sub>2</sub> discharges (blue markers) feature net retention while He discharges (red markers) have net removal. The analysis includes the gas introduced via valves as well as inboard and outboard launched pellets. The pumped gas amount is obtained by time integrating the gas pressure, an averaged signal from 20 gauges located in the pumping ducts, multiplied by the effective pumping speed for He and H<sub>2</sub>. The pumped gas is assumed to be either all He or all H<sub>2</sub> in respective He and H<sub>2</sub> pulses. This approach is justified in this plot as it overestimates the pumped amount in H<sub>2</sub> pulses in case of impurities outgassing. Impurities are pumped at a lower rate than H<sub>2</sub>. It also overestimates the pumped amount in He pulses in case of H<sub>2</sub> outgassing but only slightly; He is pumped about 10% faster than H<sub>2</sub>.

The net retention in H<sub>2</sub> discharges is explained by trapping of hydrogen in He-conditioned walls, codeposition with eroded material and

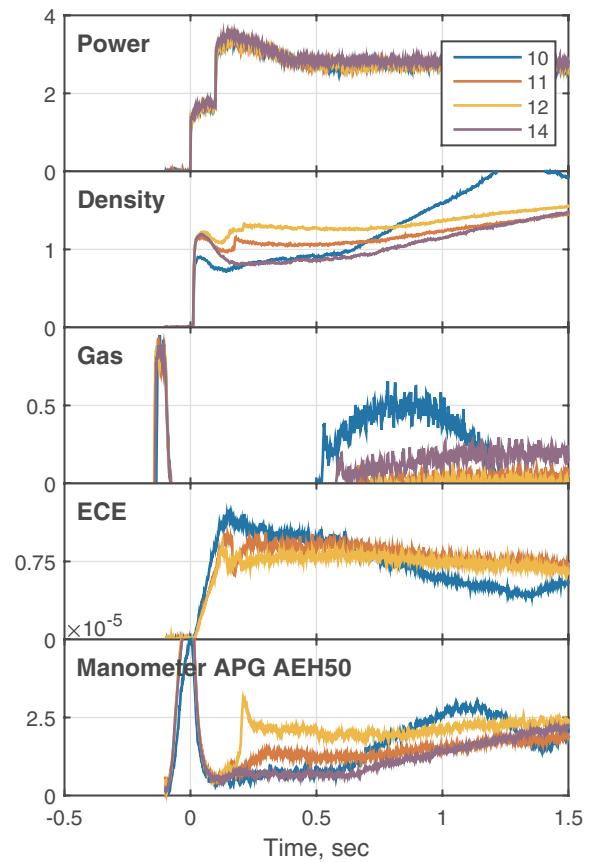


**Fig. 2.** Mass spectrometry intensities for subsequent H<sub>2</sub>-GDC's procedures from campaign start to end as function of cumulated H<sub>2</sub>-GDC time. The black dashed grid lines show time dependency ( $t^{-0.7}$ ), the red dashed lines indicate ECRH operation days.

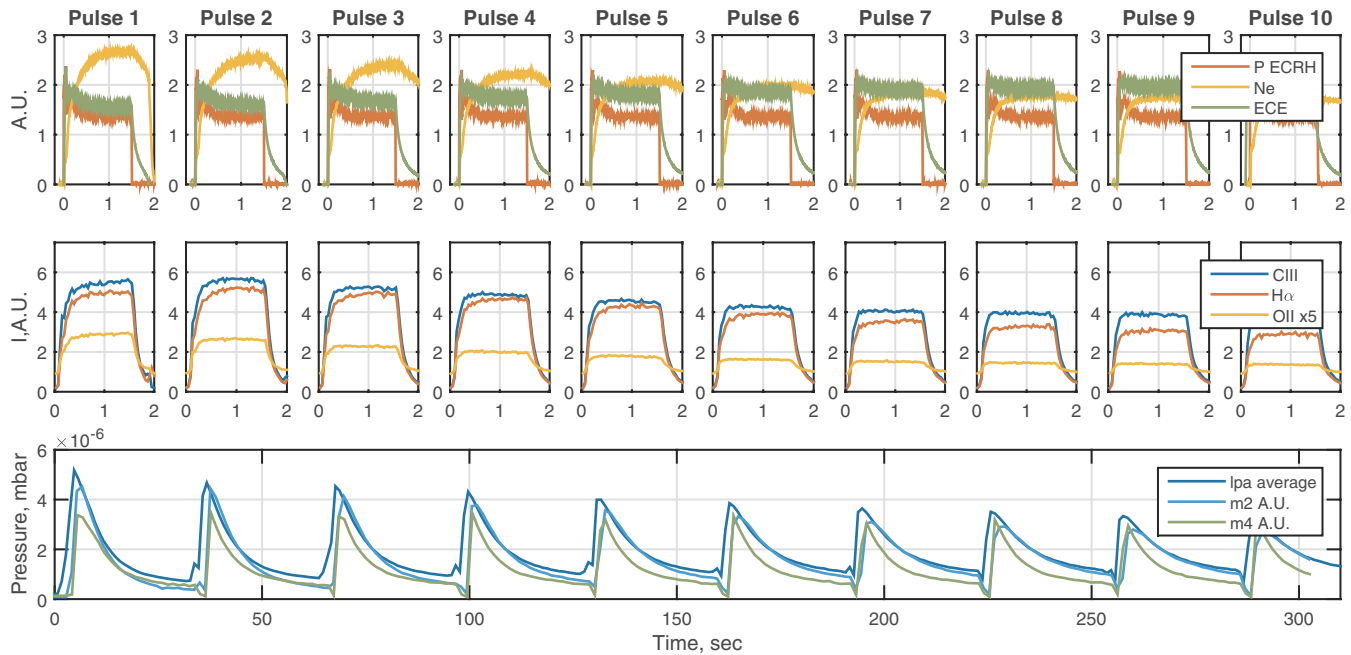


**Fig. 3.** Gas balance for all ECRH experiments of OP1.2a. He and H<sub>2</sub> discharges are shown as red and blue markers respectively.

implantation in the PFC. Net removal in He discharges is understood from complete recycling of helium and additional plasma induced desorption of hydrogen. These phenomena, known and observed on many fusion devices with carbon PFC [9], make controlling the hydrogen content in the PFC's throughout an operational day rather challenging. It is nevertheless needed in order to control the plasma density, a prerequisite for stellarator operation. The limited efficiency of plasma core fueling by OP1.2a main gas valves makes controlling the fuel recycling at the plasma facing components particularly important [10]. Fig. 4 shows density, feedback gas flow and manometer pressure



**Fig. 4.** Effect of wall saturation in subsequent H<sub>2</sub>-ECRH pulses EX20171121 [10–12] on density, feedback controlled gas flow, ECE temperature and manometer pressure. Illustration of recovered conditions in pulse following He conditioning EX20171121.14.



**Fig. 5.** Conditioning sequence EX20171121.39 consisting 10 pulses of 1.5 s at modest power of 1.5 MW with 30 s pulse interval. Ongoing recovery is apparent from interferometry density, ECE temperature, passive spectroscopy for hydrogen, carbon and oxygen, and H<sub>2</sub> partial pressure QMS.

of 4 subsequent H<sub>2</sub> discharges on W7-X with identical ECRH power and gas prefill. Clearly density increases, gas consumption decreases, ECE temperature decreases and in-vessel gas pressure by manometers [11] increases in the first 3 H<sub>2</sub> pulses. The 4th pulse (ECE not available), preceded by a recovery discharge in He (not shown), recovered initial conditions of the 1st pulse. The effect is most visible in time window 0.1–0.6 s where the gas prefill is complemented by wall fuelling only.

### 3.2. Helium ECRH conditioning

Two types of He ECRH wall conditioning procedures were studied in the first divertor campaign of W7-X: (i) medium to high energetic “single He recovery discharges” and (ii) sequences of 10–20 short low to medium power discharges with fixed duty cycle, labelled as “pulse trains”. The latter type is found most efficient in terms of removal [12]. The interferometry density, QMS H partial pressure and characteristic radiation for hydrogen, carbon and oxygen from passive spectroscopy decreases from pulse to pulse while the ECE temperature increases, indicating the progressing conditioning (Fig. 5). Performing short discharges with idle time between pulses for evacuating the removed gas reduces also the migration and redeposition of H or impurities during the conditioning discharge procedure [13]. Each of the 10 pulses in the sequence shown in Fig. 5 had a short duration of 1.5 s at modest power of 1.5 MW. The pulse lengths (1–5 s) and the time interval between ECRH pulses (10–60 s) will be subject for further optimization in the next campaign.

When the wall is strongly loaded, i.e. when He-conditioning is required, naturally outgassing will be strong and a radiative collapse during the conditioning discharge can be a concern. A radiative collapse occurs (i) when the plasma density approaches the empirical density limit  $n_c \sim p^{0.5}$  [14] or (ii) when a negative power balance in the plasma core or locally in the edge crushes the plasma-stored energy. Cooling of the plasma center may originate from impurity accumulation or over-fuelling (e.g. by pellets) while edge cooling may follow additionally from strong outgassing combined with poor core fuelling efficiency. It is experienced that the single He recovery discharges which are generally longer (> 3 s) and use higher power (> 3 MW) compared to the pulse train discharges (< 2 s and < 3 MW) are more prone to a radiative collapse. This is in agreement with earlier limiter operation

observations where the achievable pulse length is determined by the injectable energy [7]. For same poor wall conditions one can sustain a high power discharge for a short duration, or a low power discharge for a long duration. Modelling this effect by 0D particle and energy balances is however not straightforward; it requires describing the exchange of particles and energy between the plasma core, the plasma edge and the PFCs which all may involve non-linear effects, such as surface temperature effects at the PFC. When a radiative collapse occurs in a single conditioning discharge, a second He pulse is required from experience. Conditioning by pulse trains generally allows for more efficient use of the experimental time on W7-X.

### 3.3. Helium GDC

The total net hydrogen retention in the first 3 pulses shown in Fig. 4 amounts to 124 mbar.l. These discharges were the first H<sub>2</sub> pulses following a 20 min He-GDC procedure. The single He recovery discharge, though recovering conditions for the next hydrogen pulse, removed only 11 mbar.l of hydrogen (Table 1). Although He-ECRH conditioning was further optimized to maximize removal, favoring pulse trains as best procedure, it is experienced that He-GDC between experimental days is still much needed to offset the hydrogen inventory build-up in the PFCs throughout an operation day as well as to avoid the accumulation of impurities. The duration of the He-GDC procedures ranged from 20 to 45 min at 1–1.5 A per anode, 210 V and  $3.8 \times 10^{-3}$  mbar. The optimization of the procedure is presented in [12]. The GDC is ignited in H<sub>2</sub>, as this is more stable given the maximum allowed anode voltage of 3 kV and achievable pressure of  $5 \times 10^{-2}$  mbar. Within 5 min hereafter, the working gas is changed to helium. This procedure

**Table 1**  
Illustration of H<sub>2</sub> and He gas balance of 5 subsequent pulses.

#	Experiment	Gas	Retention, mbar.l	
			H <sub>2</sub>	He
Ex20171121.10–12		H <sub>2</sub>	124	–15.5
Ex20171121.13		He	–11	–2.4
Ex20171121.14		H <sub>2</sub>	6.5	–3



renders however quantifying the hydrogen retention mitigation by He-GDC impossible. The short  $H_2$ -glow retains hydrogen in the PFC. Additionally the content in the gas feeding lines is only gradually changed over from  $H_2$  to He. QMS data shows that besides H removal, the He-GDC also reduces the  $CH_4$ , CO, and  $CO_2$  content in the vessel.

Table 1 shows that all ECRH discharges, both in  $H_2$  and in He, have net removal of helium from the PFC's. The helium concentrations in hydrogen pulses are most apparent in the first pulses right after the He-GDC. Helium to hydrogen characteristic line ratios ( $HeI/(HI + HeI)$ ) of up to 0.1 are reported [15]. Stainless steel protection panels are thought to dominate the retention of helium by GDC on W7-X. While He retention in graphite was reported at LHD [16], He retention in graphite on W7-X seems modest based on the observed positive gas balance in the diverted He plasmas (Fig. 3). Net removal of helium during ECRH pulses may therefore indicate interaction with the protection panels, through charge exchange or dissociation neutrals. If this is the case, then hydrogen and impurity accumulation on these (cold) stainless steel panels throughout an operational day may likewise be a concern, requiring dedicated conditioning efforts throughout the day; e.g. by ICRF conditioning or boronization. Finally also erosion of stainless steel by He-GDC was observed when comparing characteristic radiation spectra of before and after the He-GDC [12].

#### 4. Wall temperature and outgassing

##### 4.1. Impurity outgassing

As a result of passive cooling to ambient temperature ( $\sim 28^\circ C$ ) significant variations in the PFC temperature throughout an operational day are observed. Thermocouples (TC) that monitor the graphite tiles and underlying support structure of the divertor registered temperatures up to  $526^\circ C$ . Fig. 6a shows a typical divertor temperature evolution throughout an operational day for the 40 (of 160) most responsive TC locations (separate black lines). It is immediately clear that there are large temperature gradients along the components. Some locations heat up strongly during an ECRH discharge, indicated by red (He) and blue ( $H_2$ ) vertical dashed lines, adding up to  $100^\circ C$  to the initial temperature. The highest temperature difference, final minus

initial temperature, recorded throughout the campaign is  $356^\circ C$ . Other locations are heated by heat diffusion through the materials. The temperature of these locations increases slowly by  $30$ – $60^\circ C$  throughout the day. The cyan line indicates the average of the 40 measurements.

Outgassing from the PFC as well as transport of species in material or on surfaces is strongly temperature dependent. A process with activation energy of 1 eV will become  $>30x$  stronger with a temperature increase from  $30^\circ C$  to  $60^\circ C$ . Fig. 6b shows the main impurity time traces throughout an operational day. The  $H_2O$  background pressure correlates as expected qualitatively to the averaged TC temperature. While the  $H_2O$  pressure drops during an ECRH pulse, whereafter it quickly recovers, both CO and  $CH_4$  are strongly released during a pulse.  $CH_4$  is pumped quickly after the discharge. The CO signal decays however slowly over about 1 order of magnitude in 20 min, seemingly correlated to the passive cooling rate of the hottest TC locations. Due to the high discharge repetition rate on W7-X this results in a CO background pressure increase of about one order of magnitude during the day. The increase of the oxygen content in the neutral gas will be mitigated in future campaigns on W7-X by active cooling of the PFC's, by applying boronization to getter the oxygen, and discharge conditioning such as  $H_2$ -GDC or ICRF conditioning. Deliberate heating of the divertor by ECRH discharges can be considered as localized baking tool. The highest energy throughput is achievable by applying pulse trains.

##### 4.2. Hydrogen outgassing

The PFC temperature naturally also affects the recycling of hydrogen during a plasma discharge and the continued outgassing after a discharge. Repeating identical pulses, in case of actively cooled PFC, one expects the hydrogen outgassing to increase from pulse to pulse due to a progressing saturation of the PFC's. Once saturation is achieved the outgassing stays constant. Fig. 7 shows the outgassing of a series of 23 nearly identical pulses of 2 s duration, with 2.5 MW ECRH power and 6 mbar.l injected  $H_2$  gas. The time axis zero point is set at the discharge termination. The total outgassing from pressure gauges and hydrogen outgassing from QMS is given on Fig. 7a and 7b respectively. The averaged temperature throughout the pulse, calculated as in Fig. 6a, is indicated as a subplot with same color-coding as the pressure time

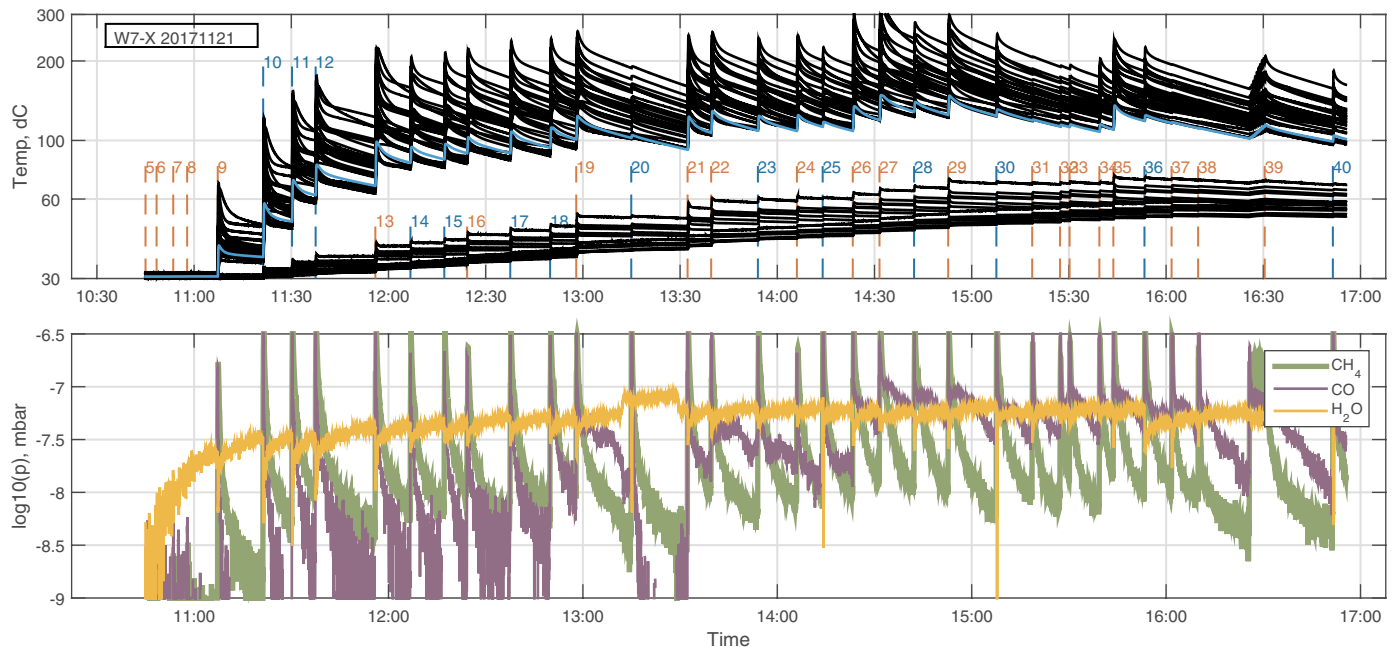
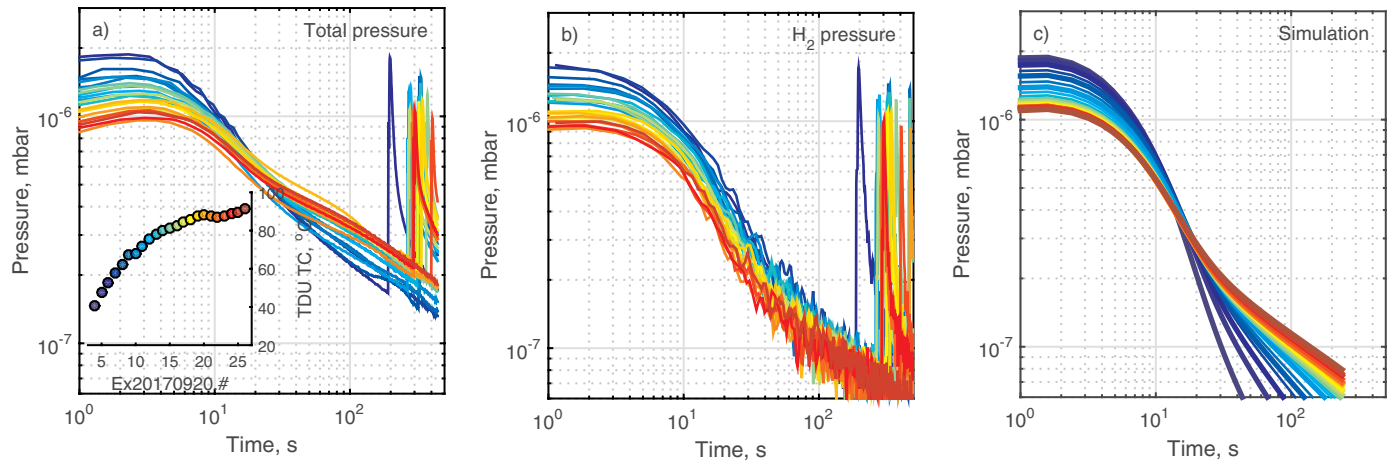


Fig. 6. Divertor temperature from thermocouples (top) and impurity outgassing from QMS (bottom) throughout an operational day (20,171,121). Vertical dashed lines in top figure indicate ECRH pulses: red for He-discharges, blue for  $H_2$  discharges. The cyan line represents the averaged temperature over the 40 most responsive thermocouples (i.e. black lines).



**Fig. 7.** Outgassing after a pulse for a series of 23 nearly identical pulses as function of the wall temperature (Ex20170920.04–26). Left: total outgassing from pressure gauges, center: hydrogen outgassing from QMS, right: simulated outgassing. Wall temperature in each pulse is given in as sub-axes on the left plot indicating the color-coding of the pressure time traces.

traces. While the material temperature increases from pulse to pulse, the outgassing pressure peaks decrease. Although simulating global outgassing measurements by local outgassing is generally challenging, basic modelling can reproduce the hydrogen outgassing dependence as a temperature effect. A recombination–diffusion model is often used to describe hydrogen outgassing from PFC's [17]. Such model considers (i) atomic hydrogen implantation near the surface, (ii) atomic hydrogen diffusion inside of the material and (iii) hydrogen recombination at the material surface. The outgassing rate  $q(t)$  is given by

$$q(t) = \frac{D}{2} \left( \frac{\partial u}{\partial t} \right) = K_r u^2$$

with  $u$  the hydrogen density at the surface,  $D = D_0 \exp(-E_D/kT)$  the effective diffusion coefficient with  $T$  the material temperature,  $E_D = 0.4\text{--}0.9$  eV the energy barrier for hydrogen jumps between two lattice points and  $D_0 = 10^{-11}\text{--}10^{-4}$  m<sup>2</sup>/s [18], and  $K_r = K_0 \exp(-E_R/kT)$  the recombination coefficient. Fig. 7c shows a tentative outgassing simulation of the 23 subsequent pulses with  $D_0 = 5 \times 10^{-6}$  m<sup>2</sup>/s and  $E_D = 0.6$  eV. The surface interaction area is fixed at 10 m<sup>2</sup>, the approximate plasma wetted area at the island divertor. The recombination coefficient  $K_0 = 4.5 \times 10^{-6}$  m<sup>4</sup>/s and  $E_R = 0.35$  eV are fitted to reproduce the pressure outgassing trend and correspond closely to the reported  $K_r = 5 \times 10^{33}$  m<sup>4</sup>/s on JET at 320 °C [19], while the resulting particle flux entering the surface ( $\sim 6$  nm), equals  $6.5 \times 10^{18}$  m<sup>2</sup>/s. The simulation reproduced the pulse-to-pulse decrease of the pressure peak as observed in both total pressure and the hydrogen pressure from QMS. The outgassing tail increases with increasing wall temperature for both the total pressure and the simulation while this is much less pronounced for the measured hydrogen pressure. The absolute values of the simulated hydrogen pressure tails correspond better to the measured hydrogen pressure than to the total the pressure.

## 5. Conclusion

Controlling the recycling of hydrogen and the release of impurities from the plasma facing components proved to be essential and challenging throughout the first divertor campaign on W7-X. One week of baking at 150 °C was applied before the campaign to successfully desaturate the PFC's from water and hydrocarbons, followed by 50 min of H<sub>2</sub>-GDC to remove mainly carbon oxides. Removal in these both procedures follows an approximate  $t - 0.7$  dependency, except for methane that is continuously produced by chemical sputtering in H<sub>2</sub>-GDC. Neither ECRH plasma operation nor He-GDC operation significantly affect the observed  $t - 0.7$  envelope curve that continues over the total 16.5 h of H<sub>2</sub>-GDC during the campaign. In future campaigns, extensive

GDC operation will be performed before ECRH plasma operation as GDC in H<sub>2</sub> is now fully commissioned.

H<sub>2</sub> ECRH discharges are shown to feature net retention while He discharges have net removal. Experimental programs in hydrogen are therefore interlaced with He discharges to desaturate the wall from hydrogen, recover good recycling conditions and hence establish plasma density control. Optimized He ECRH wall conditioning procedures consisted of sequences of 10–20 short low to medium power discharges with fixed duty cycle. These discharges experienced a low probability for a radiative collapse, which would cancel the remainder of the procedure. The time between pulses serves to evacuate the wall-released gas mitigating migration and redeposition. He-GDC remained needed between each experimental day to fully offset the hydrogen inventory build-up. The He-GDC removes as well impurities such as CH<sub>4</sub>, CO and CO<sub>2</sub>. Drawbacks of this procedure are however He retention in the stainless steel panels as well as sputtering and redistribution of stainless steel components. Substituting He-GDC by ICRF conditioning may be studied in future.

A significant increase in the averaged divertor temperature is observed throughout an operational day as a result of the passive cooling to ambient temperature. The H<sub>2</sub>O background pressure increases approximately proportional to the averaged TC temperature. CO outgassing seemingly relates to the temperature of the hottest TC locations. The increase of the oxygen content in the neutral gas affects plasma operation. It will be mitigated in future W7-X campaigns by applying boronization to getter the oxygen, by active cooling of the PFC's, and by discharge conditioning such as H<sub>2</sub>-GDC or ICRF conditioning. The PFC temperature also affects recycling of hydrogen. Preliminary recombination-diffusion modelling of hydrogen outgassing suggests enhanced diffusion to deeper surface layers with increasing wall temperature, which results in better wall pumping. This indicates that the experienced plasma performance degradation throughout an operational day results from increased impurity outgassing at higher wall temperature rather than hydrogen saturation of the wall.

## Conflict of 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.

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