WPS1-CPR(18) 18916

T Wauters et al.

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

Preprint of Paper to be submitted for publication in Proceeding of 23rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (PSI-23)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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

Tom Wauters[a,*], Andrei Goriaev[a,b], Arturo Alonso[c], Juergen Baldzuhn[d], Rudolf Brakel[d], Sebastijan Brezinsek[e], Andreas Dinklage[d], Heinz Grote[d], Joris Fellinger[d], Oliver P. Ford[d], Ralf König[d], Heinrich Laqua[d], Dmitry Matveev[e], Torsten Stange[d], Lilla Vanó[d] and the W7-X team

[a] *Laboratory for Plasma Physics, LPP-ERM/KMS, Partner of the Trilateral Euregio Cluster (TEC), Brussels, Belgium*

[b] *Department of Applied Physics, Ghent University, Belgium*

[c] *Laboratorio Nacional de Fusión, CIEMAT, Av. Complutense 40, 28040 Madrid, Spain*

[d] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[e] *Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany*

*Corresponding author: t.wauters@fz-juelich.de

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 H2 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. Optimised 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 H2O. Preliminary recombination-diffusion modeling 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.

Keywords:

1. Introduction

The first divertor campaign of Wendelstein 7-X (OP1.2a) addressed (i) the verification of the island divertor configuration and the symmetrisation 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. Boronisation 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^2, fine graphite baffle: 33 m^2, stainless steel panels of the poloidal closure: 10 m^2, fine graphite toroidal closure: 3 m^2, stainless steel panels protecting the pumping gap : 10m^2) and the first wall protection system with 50 m^2 of fine graphite tiles clamped to CuCrZr cooling structures and 70 m^2 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 second-harmonic absorption at B_0 = 2.5 T [4]. The free volume of the plasma vessel is about 110 m^3 with a plasma volume of 30 m^3. 30 turbo molecular pumps provide vacuum with an effective pumping speed in the vessel of about 40 $m^3\ s^{-1}$ for H2 [5]. The experimental arrangement for GDC on W7-X involves 10 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 de-energised. H2-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 H2O is the main outgassed species, with about 10^{25} H2O molecules removed throughout the procedure. CO and CO2, the next most prominent molecules, are released at >10x 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 Figure 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 (Figure 1b) such 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. In time it becomes increasingly difficult recover molecules from the vessel. Therefor, operating W7-X with hot walls, a technical capability of W7-X, 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 1.5×10^{-7} mbar only. This is still approximately 10% of the H2 or He filling pressure in W7-X ECRH discharges.

[Figure 1, one column wide.]

2.2. Hydrogen GDC

Hydrogen GDC, applied after the baking, 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 [7]. Figure 2 shows QMS intensities for mass m over charge q signals corresponding to CH4 (m/q=16), H2O (18), CO (28), Ar (40) and CO2 (44) for subsequent H2-GDC's procedures as function of the cumulated GDC time. The signals are normalized to the applied glow current (1-1.5A/anode). About 10^{23} – 10^{24} molecules of CO are removed. The expected $t^{-0.7}$ outgassing trend is added as multiple black dashed lines. The vertical red dashed lines indicate ECRH operation days, with discharges in H2 and He, which are typically preceded by 20 to 45 minutes of He-GDC. The first ECRH plasma operation took place after 50 minutes of H2-GDC. The last H2-GDC was performed before the last operations week of the campaign. It is concluded that ECRH operation as well as He-GDC 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 H2 was challenging and radiative collapses occurred frequently.

[Figure 2, two columns wide.]

3. Wall desaturation by Helium conditioning

3.1. Gas balance

Figure 3 plots the pumped amount of gas vs. the injected amount of gas for all experiments in OP1.2a. It clearly illustrates that generally H2 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 H2. The pumped gas is assumed to be either all He or all H2 in respective He and H2 pulses. This approach is justified in this plot as it overestimates the pumped amount in H2 pulses in case of impurities outgassing. Impurities are pumped at a lower rate than H2. It also overestimates the pumped amount in He pulses in case of H2 outgassing but only slightly; He is pumped about 10% faster than H2.

[Figure 3, one column wide.]

The net retention in H2 discharges is explained by trapping of hydrogen in He-conditioned walls, codeposition with eroded material and 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 [8], 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 [9]. Figure 4 shows density, feedback gas flow and manometer pressure of 4 subsequent

H2 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 [10] increases in the first 3 H2 pulses. The 4th pulse (ECE not available), preceded by a recovery discharge in He (not shown), clearly recovered initial conditions of the 1st pulse.

[Figure 4, one column wide.]

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 to 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 [11]. 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 (Figure 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 [12]. Each of the 10 pulses in the sequence shown in Figure 5 had a short duration of 1.5s at modest power of 1.5MW. The pulse lengths (1 to 5 s) and the time interval between ECRH pulses (10 to 60 s) will be subject for further optimization in the next campaign.

[Figure 5, two columns wide.]

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 $n_c \sim P^{0.5}$ 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-fueling (e.g. by pellets) while edge cooling may follow additionally from strong outgassing combined with poor core fueling efficiency. It is experienced that the single He recovery discharges which are generally longer (>3s) and use higher power (>3MW) compared to the pulse train discharges (<2s and <3MW) 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 [13]. For same poor wall conditions one can sustain a high power discharge for a short duration, or a low power discharge for a large duration. Modeling 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 PFC's 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 figure 4 amounts to 124 mbar.l. These discharges were the first H2 pulses following a 20 minutes He-GDC procedure. The single He recovery discharge, 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 minutes at 1-1.5A per anode, 210V and $3.8x10^{-3}$ mbar. The optimisation of the procedure is presented in [11]. The GDC is ignited in H2, as this is more stable given the maximum allowed anode voltage of 3 kV and achievable pressure of $5x10^{-2}$ mbar. Within 5 minutes hereafter, the working gas is changed to helium. This procedure renders however quantifying the hydrogen retention mitigation by He-GDC impossible. The short H2-glow retains hydrogen in the PFC. Additionally, the content in the gas feeding lines is only gradually changed over from H2 to He. QMS data shows that besides H removal, the He-GDC also reduces the CH4, CO and CO2 content in the vessel.

Table 1 shows that all ECRH discharges, both in H2 and in He, have net removal of helium from the PFC's. He removal is found most apparent in the first pulses right after the He-GDC. Helium to hydrogen characteristic line ratios (HeI/(HI+HeI)) in H2-ECRH pulses of up to 0.1 are reported [14]. It is thought to originate from He retention in the stainless steel protection panels, as He retention in carbon is modest. He removal during ECRH pulses then indicates interaction with these panels, possibly through charge exchange neutrals or H2 dissociation fluxes. If this is the case, then hydrogen and impurity accumulation on the (cold) stainless steel protection panels throughout an operational day may also be a concern, requiring dedicated conditioning efforts throughout the day; e.g. by ICRF conditioning or boronisation. Finally also erosion of the stainless steel by He – GDC was observed when comparing characteristic radiation spectra of before and after the He-GDC [11].

[Table 1, one column wide.]

4. Wall temperature and outgassing

4.1. Impurity outgassing

As a result of passive cooling to ambient temperature (~28°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°C. Figure 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 (H2) vertical dashed lines, adding up to 100°C to the initial temperature. The highest temperature difference, final minus initial temperature, recorded throughout the campaign is 356°C. Other locations are heated through heat diffusion through the materials. The temperature of these locations increases slowly by 30 to 60°C throughout the day. The cyan line indicates the average of the 40 measurements.

[Figure 6, two columns wide.]

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°C to 60°C. Figure 6b shows the

main impurity time traces throughout an operational day. The H2O background pressure increases approximately proportional to the averaged TC temperature. While the H2O pressure drops during an ECRH pulse, whereafter it quickly recovers, both CO and CH4 are strongly released during a pulse. CH4 is pumped quickly after the discharge. The CO signal decays however slowly over about 1 order of magnitude in 20 minutes, 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 boronisation to getter the oxygen, and discharge conditioning such as H2-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 recycling

The PFC temperature naturally also affects recycling of hydrogen. Repeating identical pulses, in case of actively cooled PFC, one expects the hydrogen-recycling to increase from pulse to pulse due to a progressing saturation of the PFC's. Once saturation is achieved the outgassing stays constant. Figure 7 shows the outgassing of a series of 23 nearly identical pulses. The total outgassing from pressure gauges and hydrogen outgassing from QMS is given on Figure 7a and 7b respectively. The averaged temperature throughout the pulse, calculated as in figure 7a, is indicated as a subplot with same color-coding as the pressure time 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 modeling can reproduce the dependence of hydrogen recycling as a temperature effect. A recombination-diffusion model is often used to describe hydrogen outgassing from PFC's [15]. 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 = 0.4-0.9 eV the energy barrier for hydrogen jumps between two lattice points and D_0 = 10^{-11}-10^{-4} m²/s [16], and $K_r = K_0 \exp(-E_R/kT)$ the recombination coefficient. Figure 8c shows a tentative outgassing simulation of the 23 subsequent pulses with D_o = 5x10^{-6} m²/s and E_D = 0.6eV. The surface interaction area is fixed at 10m², the approximate plasma wetted area at the island divertor. The recombination coefficient K_0= 4.5x10^{-6} m⁴/s and E_R = 0.35eV are fitted to reproduce the pressure outgassing trend and correspond closely to the reported K_r=5x10^{33}m⁴/s on JET at 320°C [17], while the resulting particle flux entering the surface (~6nm), equals 6.5x10^{18}/m²s. 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.

[Figure 7, two columns wide.]

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 minutes of H2-GDC to remove mainly methane and carbon oxides. Removal in these both procedures follows an approximate $t^{-0.7}$ dependency. Neither ECRH plasma operation nor He-GDC operation significantly affect the observed $t^{-0.7}$ envelope curve that continues over the total 16.5 hours of H2-GDC during the campaign. In future campaigns, extensive GDC operation will be performed before ECRH plasma operation as GDC in H2 is now fully commissioned.

H2 ECRH discharges are shown to feature net retention while He discharges have net removal. Experimental programs in hydrogen are therefor interlaced with He discharges to desaturate the wall from hydrogen, recover good recycling conditions and hence establish plasma density control. Optimised He ECRH wall conditioning procedures consisted of sequences of 10 to 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 CH4, CO and CO2. 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 H2O 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 boronisation to getter the oxygen, by active cooling of the PFC's, and by discharge conditioning such as H2-GDC or ICRF conditioning. The PFC temperature also affects recycling of hydrogen. Preliminary recombination-diffusion modeling 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.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium

and has received funding from the EURATOM research and training programme 2014 – 2018 under grant agreement no. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] R. C. Wolf et al., EPS Conference on Plasma Physics, Prague, July 4 2018

[2] A. Peacock et al., Progress in the design and development of a test divertor (TDU) for the start of W7-X operation, Fus. Eng Des. 84 (2009) 1475–1478

[3] J Boscary et al., Design and technological solutions for the plasma facing components of WENDELSTEIN 7-X, Fusion Engineering and Design 86 (2011) 572–575

[4] Erckmann V. et al 2007 Fusion Sci. Technol. 52 291

[5] Grote H. et al 2003 J. Nucl. Mater. 313–6 1298–303

[6] Spring A. 2003 Fusion Eng. Des. 66–8 371–5

[7] H. F. Dylla, AIP Conference Proceedings 199, 3 (1990); https://doi.org/10.1063/1.39072

[8] Ehrenberg et al., Journal of Nuclear Materials Volumes 162–164, 1 April 1989, Pages 63-79

[9] T. Sunn Pedersen et al., EPS Conference on Plasma Physics, Prague, July 4 2018

[10] U. Wenzel et al., 2017 *JINST* **12** C09008, https://doi.org/10.1088/1748-0221/12/09/C09008

[11] A. Goriaev et al., this conference

[12] T. Wauters et al., Journal of Nuclear Materials, Volume 415, Issue 1, Supplement, 1 August 2011, Pages S1033-S1036, https://doi.org/10.1016/j.jnucmat.2010.11.072

[13] T. Wauters et al., Nucl. Fusion **58** (2018) 066013, https://doi.org/10.1088/1741-4326/aab2c9

[14] Y. Wei et al., AIP Advances, accepted for publication, 2018

[15] K. Akaishi et al., Journal of Vacuum Science & Technology A **20**, 848 (2002) https://doi.org/10.1116/1.1471354

[16] R.A. Causey et al., Journal of Nuclear Materials 300 (2002) 91–117

[17] V. Philipps and J. Ehrenberg, Journal of Vacuum Science & Technology A 11, 437 (1993); https://doi.org/10.1116/1.578750

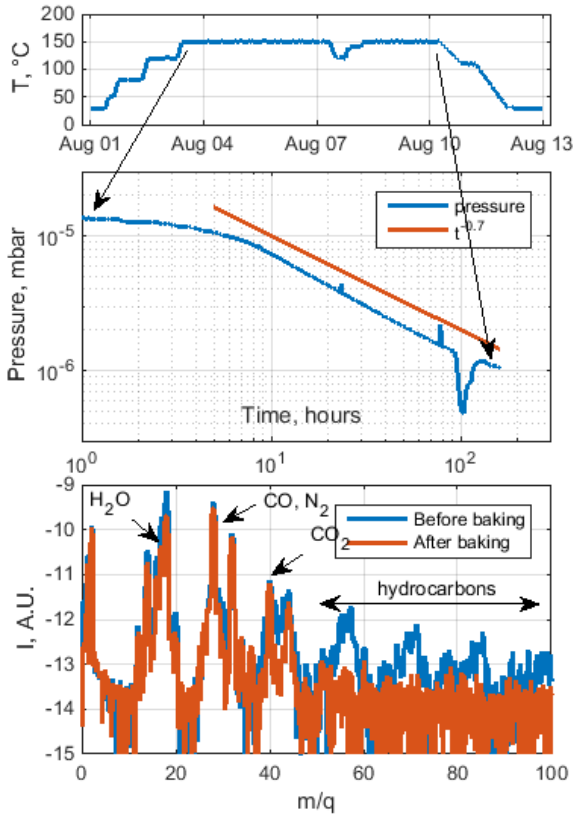

Figure 1: Baking procedure preceding first plasma operation. Top: vessel temperature in time, including about 1 week at 150°C. Middle: Pressure decay during 150°C flat top phase and $t^{-0.7}$ trend curve. Bottom: vacuum QMS spectra before (Jul 31) and after baking (Aug 12) at 28°C.

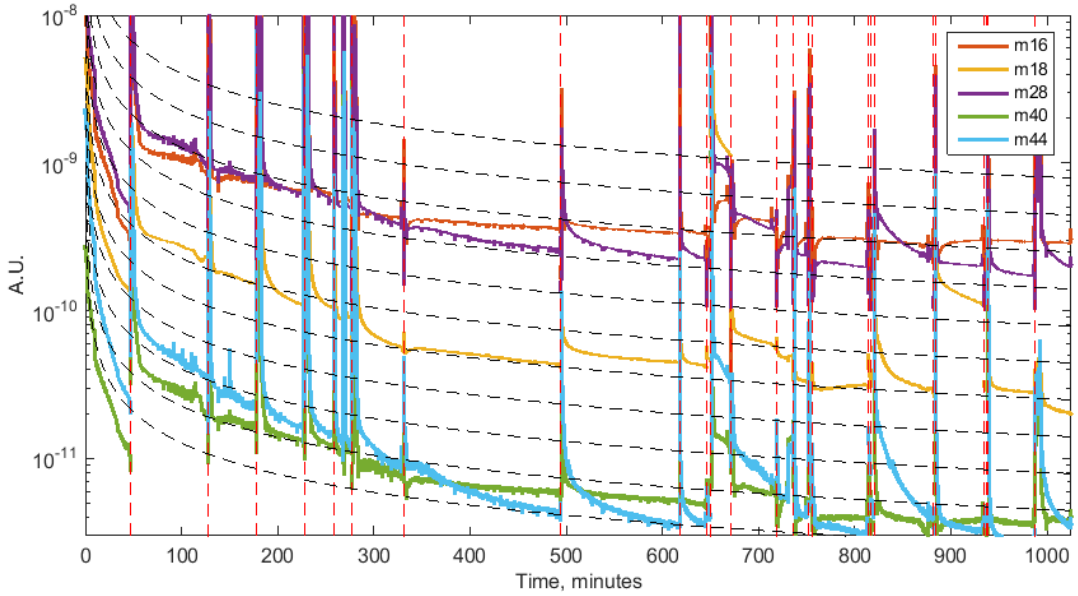

Figure 2: Mass spectrometry intensities for subsequent H2-GDC's procedures from campaign start to end as function of cumulated H2-GDC time. The black dashed grid lines show time dependency ($t^{-0.7}$), the red dashed lines indicate ECRH operation days

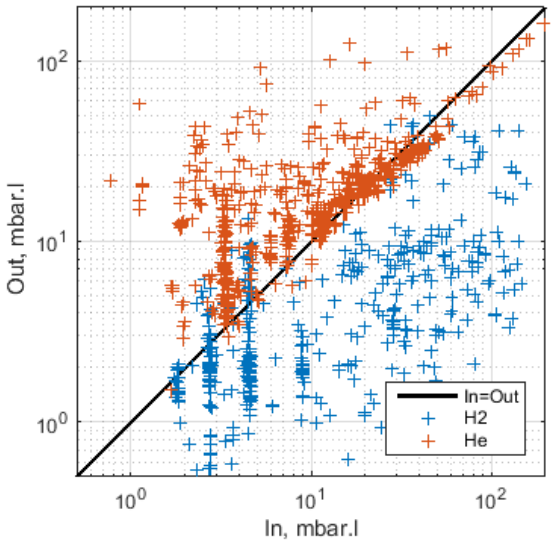

Figure 3: Gas balance for all ECRH experiments of OP1.2a. He and H2 discharges are shown as red and blue markers respectively.

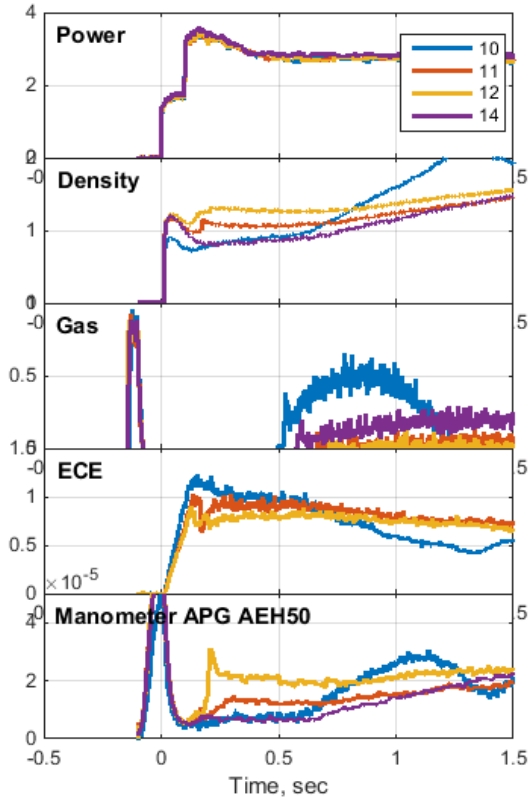

Figure 4: Effect of wall saturation in subsequent H2-ECRH pulses EX20171121.[10-12] on density, feedback controlled gas flow, ECE temperature and manometer pressure. Illustration of recovered conditions in pulse following He conditioning EX20171121.14.

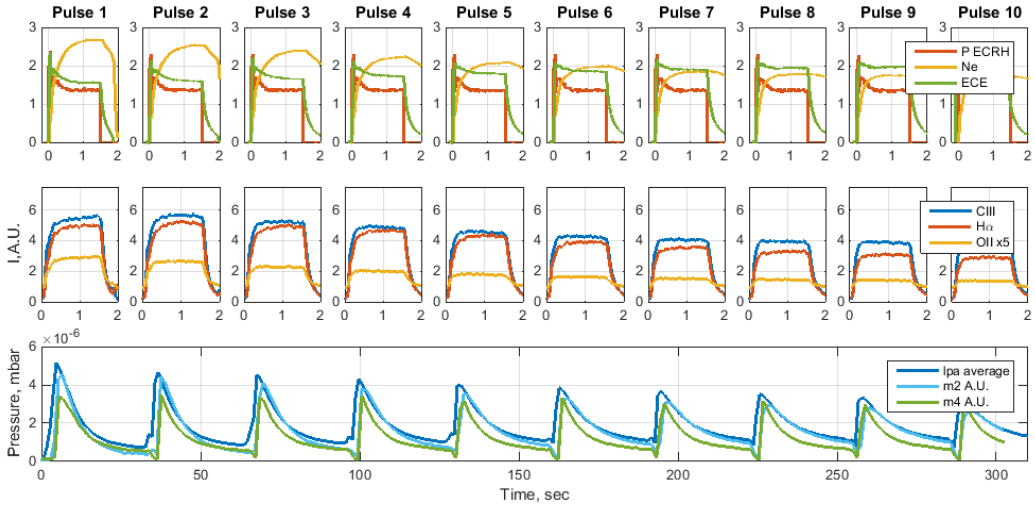

Figure 5: Conditioning sequence EX20171121.39 consisting 10 pulses of 1.5 s at modest power of 1.5 MW with 30 s pulse interval. Ongoing recovery is apparent from interferometry density, ECE temperature, passive spectroscopy for hydrogen, carbon and oxygen, and H2 partial pressure QMS.

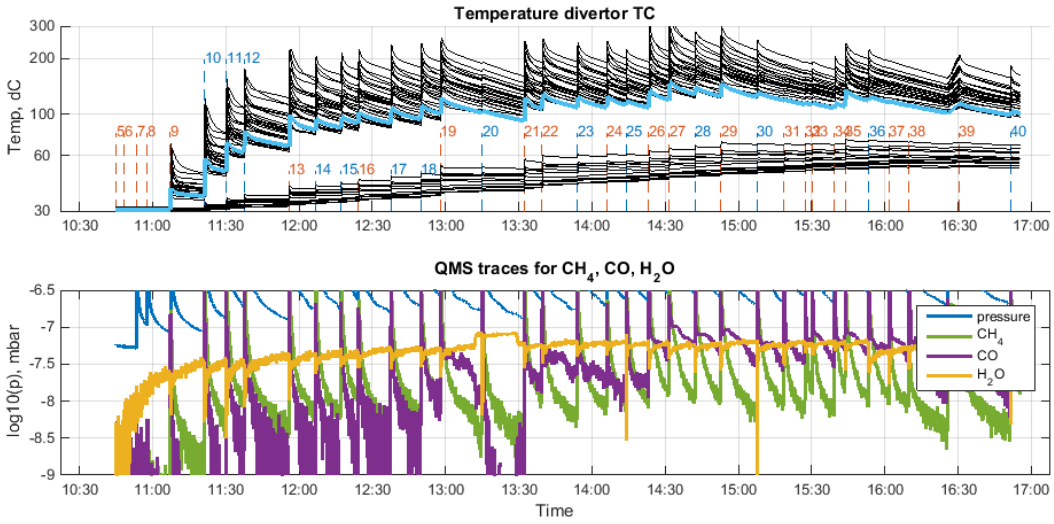

Figure 6: Relation of wall temperature and impurity outgassing throughout an operational day (20171121). Vertical dashed lines in top figure indicate ECRH pulses: red for He-discharges, blue for H2 discharges.

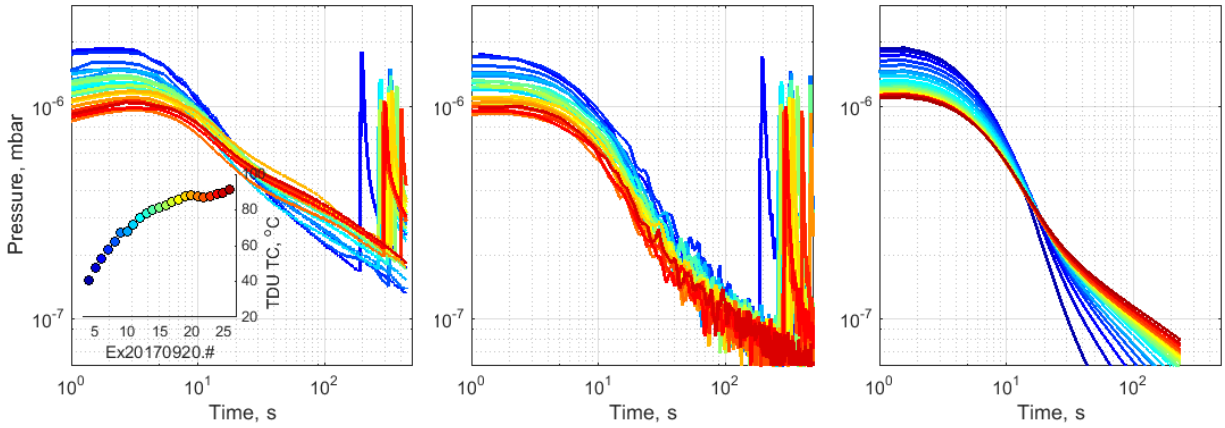

Figure 7: Outgassing after a pulse for a series of 23 nearly identical pulses as function of the wall temperature (Ex20170920.04-26). Left: total outgassing from pressure gauges, center: hydrogen outgassing from QMS, right: simulated outgassing. Wall temperature in each pulse is given in as sub-axes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

Table 1: Illustration of H2 and He gas balance of 5 subsequent pulses

Experiment		Retention, mbar.l	
#	Gas	H2	He
Ex20171121.10-12	H2	124	-15.5
Ex20171121.13	He	-11	-2.4
Ex20171121.14	H2	6.5	-3