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# Development of glow discharge and electron cyclotron resonance heating conditioning on W7-X

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ABSTRACT

For successful operation of Wendelstein 7-X (W7-X) control of plasma impurity content and fuel recycling is required. This can be achieved by using wall conditioning methods. During the first divertor operation campaign (OP1.2a) of W7-X glow discharge conditioning (GDC), weekly in hydrogen and daily in helium for impurity and hydrogen removal respectively, was used in the absence of the magnetic field. He electron cyclotron resonance heating (ECRH) discharges were applied for density control in hydrogen plasmas during experimental days. The optimization of GDC and He ECRH wall conditioning on W7-X are presented. Solutions for glow discharge ignition problems are examined. The suitable He – GDC parameters, i.e. anode current and neutral gas pressure, are defined to keep the balance between maximum possible hydrogen removal rate and minimum plasma – facing component (PFC) erosion. Sequences of short He – ECRH pulses, so-called pulse trains, has been successfully implemented. The effect of pulse train main parameter variation such as gas prefill, input power, pulse length, duty cycle is described. The efficiency of single He recovery discharges and pulse trains are compared. The results of this work show significant improvement of wall cleaning efficiency.

## 1. Introduction

The main aim of the superconducting stellarator W7-X, located at the Max-Planck-Institute in Greifswald, is to demonstrate the viability of optimized stellarators as potential fusion reactor. The sustainment of plasmas at high heating power and high confinement is vital to assess plasma operation at reactor – relevant collisionalities and plasma beta values. After successful device commissioning and first plasma start-up [1] initial operation with inboard carbon limiters and metallic wall made of stainless steel and CuCrZr, called OP1.1, was conducted [2–4]. In OP1.1, the heating energy was limited to 4 MJ, allowing up to 6 s discharges at good confinement and low bootstrap current as predicted [5]. Subsequent operational phase, OP1.2a, is accomplished with an inertially cooled graphite island divertor and fully C-covered high heat flux components (surface area of 50 $m^2$). However, the part of PFC, remain stainless steel panels (surface area of 70 $m^2$) [6]. Thirty turbomolecular pumps with an effective pumping speed of up to 36 $m^3$/s for hydrogen provide vacuum for about 110 $m^3$ plasma vessel [7,8]. During the divertor configuration the injected energy per plasma pulse is increased to 80 MJ [3]. As in the first operation phase, for OP1.2a the main heating system is electron cyclotron resonance heating (ECRH) launching microwaves at 140 GHz and providing up to 7.4 MW of power [9].

As a next step to go, actively cooled plasma facing components are required to achieve high power steady-state plasma operation at pulse lengths of up to 30 min on W7-X [10]. As found in recent operation, it is crucial to control impurity content and the plasma density. It turned out that good wall conditions positively affect the plasma performance [11]. The common tool to control surface state of plasma facing components as main source of impurities for magnetic controlled fusion device is wall conditioning [11]. The available conditioning techniques in OP1.2a were baking, glow discharge cleaning (GDC) and electron cyclotron resonance heating (ECRH) conditioning. The combination of these techniques turned out to be essential to get to good wall conditions. The optimization of the techniques and its combination is beneficial for fast achievement of good plasma performance.

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To summarize the available techniques on W7-X, baking of the vacuum vessel at the temperature of 150 °C during ∼1 week before the first plasma operation allowed to remove almost all heavy impurity species such as high hydrocarbons and to significantly reduce the amount of water and carbon oxides [12]. ECRH wall conditioning and GDC further improved the W7-X plasma performance. During the previous operational campaign in limiter configuration, OP1.1, it was shown that He GDC and ECRH wall conditioning alone can decrease the outgassing of vacuum vessel PFC by more than one order of magnitude. Good wall conditions in OP1.1 were defined by normalized outgassing, ratio between outgassing peak and input energy, value below $1 \times 10^{-9}$ mbar $kJ^{-1}$ [13]. However, it was concluded that ECRH conditioning combined with He-GDC was not time efficient for reaching these conditions [13]. In OP1.2a additionally $H_2$ – GDC was applied. A cumulative impurity removal effect of GDC in hydrogen was shown indicating that a certain number of GDC hours should be performed before plasma operation [12].

During OP1.2a, weekly performed $H_2$ – GDC could reduce the amount of impurities produced by wall components erosion, the chemical formation and leaks. He – GDC was carried out daily to desaturate the wall from hydrogen before the beginning of the experimental session [14] due to its availability only between experimental sessions when W7-X superconducting magnets are not powered. To sustain plasma density control during the whole day of plasma operation He – ECRH cleaning was done as single recovery discharges or short discharge sequences, called pulse trains. All three types of wall conditioning technique were optimized throughout OP1.2a aiming at limited execution time while keeping its maximum efficiency.

This paper gives the results of wall conditioning procedure optimization throughout the first divertor operation phase of W7-X. It also reports the encountered problems during the investigation of wall conditioning methods. The recipes for the different wall conditioning scenarios will be applied in future experimental campaigns of W7-X. This work is interdependent with the paper dedicated to overview of wall conditioning studies throughout OP1.2a on W7-X [12].

## 2. Glow discharge cleaning

The GDC system of W7-X consists of 10 calotte-shaped graphite anodes [15]. One anode is located in each half module and individually power supplied [16]. The output power of the GDC system is limited by 4.5 kW while the recommended anode current should not exceed 1.5 A [17]. The time for GDC was limited during OP1.2a due to the required manpower for GDC execution and restricted access to the W7-X torus hall during GDC operation. The dense physics program also demanded to shorten daily glow discharge wall conditioning. According to these conditions $H_2$ – GDC with duration of up to 90 min was planned as a weekly routine to reduce the amount of impurities in the vacuum vessel. The optimization of glow discharge wall conditioning meaning discharge homogeneity, stability and maximum impurity removal efficiency was required. Care was taken to avoid erosion of the plasma – facing components (PFC).

The GDC system of W7-X was not equipped by any special devices, like radiofrequency-assisted glow discharge (RG-discharge) on TEXTOR and JET [18] or a separate starting device on ASDEX Upgrade [19], to assist fast break-down reliably. Thus, break-down of glow discharge at operational pressures could not be achieved on W7-X with current GDC system configuration. The injection of noble gases with low ionization energy (i.e. argon) as a start-up assistance technique was not pursuit to avoid an increase of metallic PFC erosion.

However, the break-down of hydrogen discharge was achieved at neutral gas pressure of (3–5) $\times 10^{-2}$ mbar at voltages of 1.1–1.6 kV. It was shown in preparation studies on the TOMAS device [20] that $H_2$ – GDC is strongly inhomogeneous at pressures close to break-down pressure, so-called hollow cathode effect [21]. The discharge is localized in the anode areas and other cavities of the vacuum vessel.

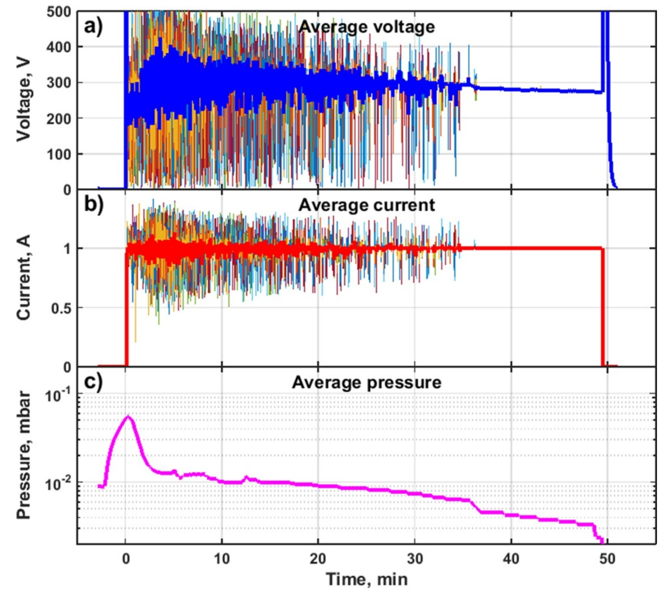


**Fig. 1.** (a) The evolution of main $H_2$ – GDC (20170823) parameters (a) anode voltage, (b) anode current and (c) neutral gas pressure. The working pressure range corresponding to GDC stability and reliable homogeneity is below $5 \times 10^{-3}$ mbar.

Moreover, the current – voltage characteristics of glow discharge strongly fluctuate at pressures above ∼ $9 \times 10^{-3}$ mbar (Fig. 1). These findings may also indicate arcing causing the damage of the vacuum vessel components. To prevent this effect the potentially break-down scheme has been adapted enabling fast discharge pressure decrease by combining a stepwise increase of the pumping speed and a decrease of gas flow. The working pressure for stable $H_2$ – GDC operation was chosen in the range of (4.4–4.5) $\times 10^{-3}$ mbar and was achieved in less than 2 min after break-down. Further pressure decrease close to the lower discharge sustainability limit improves the homogeneity of glow discharge, which can be only observed visually, and impurity removal efficiency. This is attributed to anode voltage rise (Fig. 2a). It was found, however, that the discharge operation at lower pressure leads to unstable operation of several glow discharge anodes. In order to

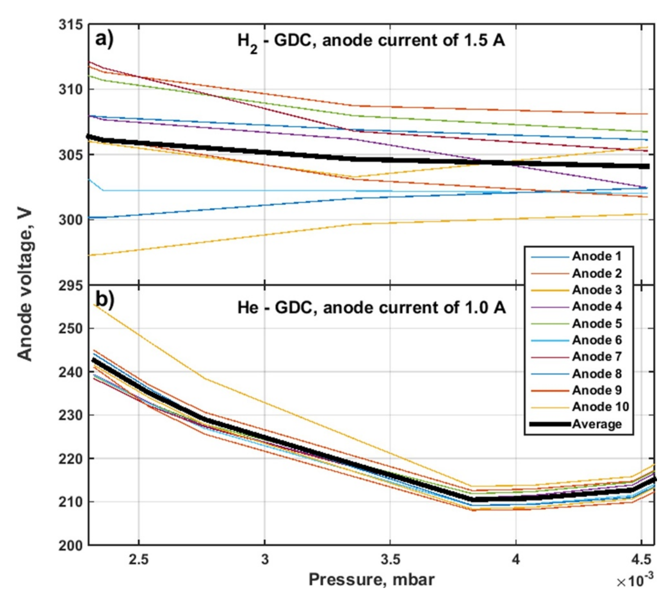


**Fig. 2.** (a) $H_2$ glow discharge anode voltage dependence on neutral gas pressure at anode current of 1.5 A. (b) He glow discharge anode voltage dependence on neutral gas pressure at anode current of 1 A.

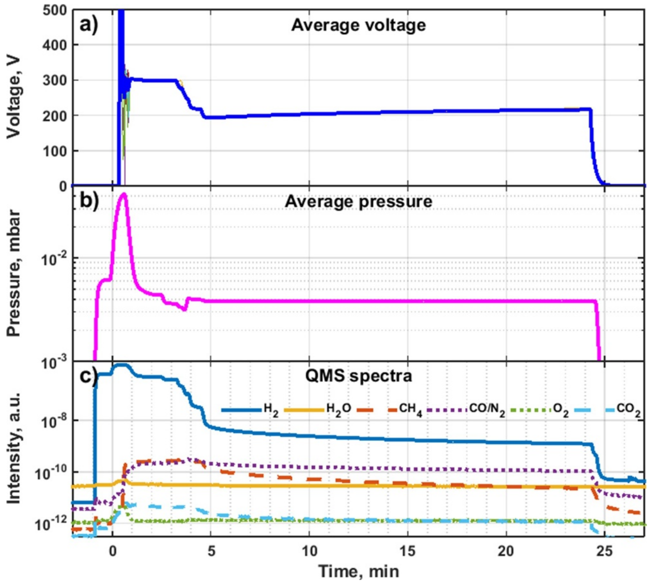


**Fig. 3.** He – GDC overview (20171109): (a) averaged anode voltage, (b) neutral gas pressure, (c) Quadrupole Mass-Spectrometer (QMS) time traces wall released molecules. The given GDC procedure was mainly used to desaturate the walls from hydrogen after a day of plasma operation. The discharge break-down was done in hydrogen, which after ~5 min was changed by helium.

achieve highest cleaning efficiency the $H_2$ – GDC was operated at upper allowed anode current limit of 1.5 A. Since the available flux of high-energetic ions towards the PFC was maximized at these settings, the duration of conditioning could be shortened.

In OP1.2a He – GDC was used as daily routine cleaning procedure to desaturate the wall of W7-X vacuum vessel from hydrogen. This procedure was conducted 20–25 min in the morning prior plasma operation. He-GDC could not be easily ignited at the maximum power supply voltage of 3 kV and pressure of (5–6) $\times 10^{-2}$ mbar. However, it has been found that it is possible to initiate the discharge in hydrogen and, after its stabilization, to change the working gas to helium. In spite the fact that it requested additional time for gas exchanges and removal of additional amount of saturated hydrogen (5–7 min) it is still a considerable improvement compared to the time spent for discharge breakdown in He. The typical He – GDC overview is shown on Fig. 3.

The problem of PFC erosion by He – GDC, previously reported in [13], remained in OP1.2a. Clear indications for sputtering were revealed by the Pulse Height Analysis diagnostic [22,23], shown in Fig. 4. The eroded wall material consists mainly of stainless steel components (Ni, Cr, Fe) redeposited during He-GDC on the plasma-facing components and, then, released during the plasma operation. To reduce the amount of eroded material the voltage of the glow discharge was reduced to its minimum possible value (Fig. 2b). The optimal working pressure for He-GDC minimizing the sputtering yields of stainless steel components was ~ $3.8 \times 10^{-3}$ mbar. The anode current for glow discharge was kept at 1 A to contribute to minimization of erosion effect by reduction of ion fluxes. Further current reduction was not beneficial due to its minor influence on anode voltage, e.g. a reduction by factor 2 to 0.5 A changes the voltage by less than 1%. It also reduces the ion flux to the PFC which increases the execution time of He-GDC to achieve the same cleaning results. Thus, to get satisfactory wall conditions before start of the plasma operation the total duration of He – GDC was no longer than 15–20 min according to limitations mentioned above: sufficient hydrogen removal at limited execution time within minimum impact on PFC erosion. Here, satisfactory wall conditions mean the almost fully suppressed wall fuelling in the first hydrogen discharge following He-GDC procedure. Quantifying hydrogen removal by He – GDC was complicated by the following reasons. First, the short start-up of GDC in hydrogen contributes to fuel retention in the PFCs.

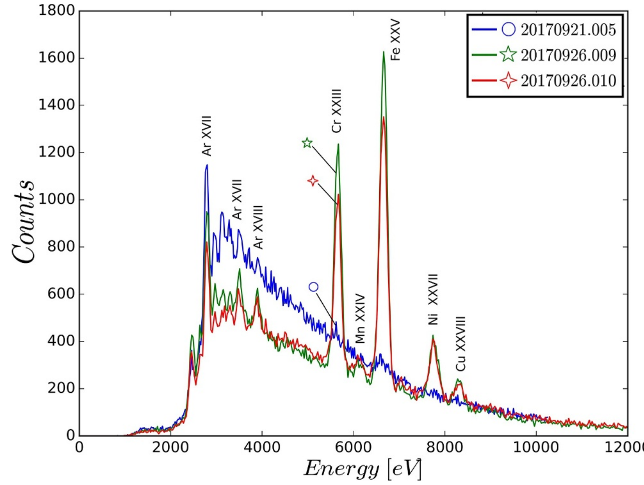


**Fig. 4.** PHA spectra before (20170921.5) and after (20170926.9 and 20170926.10) He-GDC on 20170925. The plot indicates presence and reduction of eroded and redistributed by He-GDC components of stainless steel in similar hydrogen plasma discharges after glow discharge. The discharge before GDC does not have any pronounced eroded material traces.

Second, relatively slow change of the working gas in the gas feeding lines gradually effect on the residual gas content ($He/H_2$ ratio) of GDC. Another reason is that the decay time of strong outgassing after GDC is smaller than the time between morning GDC session and start of the plasma operation.

## 3. He electron cyclotron resonance heating wall conditioning

Since glow discharges are strongly affected by the presence of magnetic field glow discharge cleaning cannot be employed. Other available methods of wall conditioning such as ECRH wall conditioning had to be adapted to provide the density control and impurity release during the plasma experiments. The preliminary studies of these methods for stellarator -like magnetic field configurations were observed on WEGA [24]. In comparison with tokamaks, e.g. KSTAR [25] and TCV [26], changes of magnetic field configurations [27] almost have no influence on ECRH power absorption. The first systematic application of ECRH – based wall conditioning methods was done on W7-X during OP1.1. All ECRH-based conditioning discharges are carried out at the second harmonic extraordinary mode (X2). The microwave absorption coefficient fluctuates around 98 ± 1.5% [28]. The break-down time is less than 10 ms for input power 1.5–2.3 MW at neutral gas pressure (He) of (3–5) $\times 10^{-5}$ mbar [29]. Nearly full absorption could be achieved within 10 ms after injecting microwaves [30]. The results of the first ECRH – based wall conditioning methods application are reported in detail in [13]. In OP1.2a the dense experimental program and the lack of other powerful methods like Ion Cyclotron Resonance Heating (ICRH) [31] enforced the further optimization and development of He – ECRH wall conditioning methods as routine tools for control of wall loading by hydrogen.

One aspect of optimization was the implementation of so-called “pulse trains”, i.e. series of short discharges at a certain duty cycle. During dwell time or pulse interval time, which is usually 10–15 times longer than pulse length, the released species are pumped down which allows to start the next pulse within less contaminated plasma. The dwell time, together with the short pulse length, strongly reduces probability of impurity/fuel atoms migration and redeposition during the plasma discharge, and therefore, the ratio between removal and redeposition can be higher than for long pulses with the same plasma parameters. Directly after sequences of short pulses wall conditions are significantly improved meaning that the performance of subsequent plasma discharges is improved. The high effectiveness of the pulse train method was proven by experiments on TEXTOR and TORE SUPRA [32].

The first pulse train optimization experiments were carried out in the beginning of OP1.2a. Unfortunately, not all main diagnostics were available at that moment. The typical pulse was represented by the sequences of short discharges (10 discharges). Each pulse train was characterized by the pulse length, pulse interval, discharge input power and gas prefill (amount of gas injected with the constant gas flow of 75 mbar.l/s in certain time). The pulse input power was chosen in the range of 1.5–2.2 MW. It was done to achieve relatively large heat and particle fluxes towards the divertor, which is the major plasma wetted area for this type of discharges, and to assist the reliable brake-down. Moreover, the usage of high power cleaning discharges shows that for stellarators ECRH – based wall conditioning at high power can be done reliably and safely, and are therefore considered relevant for future fusion devices.

The optimisation of the pulse trains was conducted at High Mirror (KJM) magnetic field configuration. Three gyrotrons were used for on-axis conditioning plasma heating. The main purpose for applying pulse trains on W7-X is desaturating the wall from hydrogen. In order to define cleaning efficiency of a pulse train, the amount of removed fuel from the wall was used as a main comparison criterion. For proper comparison of pulse train cleaning effect hydrogen partial pressure of almost all pulse train was normalized according to the removal by the first pulse of the sequence. The comparative results of the first optimization are shown on Fig. 5. Here, the cumulated QMS (Quadrupole Mass-Spectrometer) signal is an integral of QMS signal intensity over time that is proportional to the total removal of certain type of residual gas species. The integration has been done by using of trapezoidal method of numerical integration. The optimization was done by a comparison of hydrogen removal efficiencies of pulse trains with different characteristic parameters. First, two discharge sequences in He were done at different discharge input power, 2100 kW and 1600 kW, keeping the same discharge length of 1500 ms, pulse interval of 30 s and gas prefill (25 ms). In all experiments gas injection was done 100 ms before the discharge ignition and was not considered as a variable parameter. As it is clearly seen on Fig. 5a, the removal rate of hydrogen are significantly higher for the pulse train with higher input power (2100 kW). That indicates that a higher heating power leads to higher fuel removal, which results both in higher density of the plasma and higher divertor fluxes. The second considered characteristic parameter of He pulse train was the length of each pulse in the sequences. The comparison of pulse trains with the pulse lengths of 1500 ms and 750 ms shows that the same removal results can be achieved faster with longer pulses (Fig. 5b). It should be mentioned that an increase of pulse length leads to increase of the amount of released hydrogen, but it does not directly result higher removal from the vessel due to high probability of hydrogen redeposition and retention, as shown in [31]. Thus, the removal efficiency dependence on pulse length can be non-linear and its further analysis for W7-X is strongly required. In case of gas prefill as a variable experimental parameter it is found that the discharge sequence with prefill of 15 ms is slightly better than one of 25 ms (Fig. 5c). The attempt to perform a pulse train with the gas prefill of 10 ms showed that the amount of injected gas was not sufficient for reliable break-down.

Two pulse interval (30 s and 60 s) are examined. According to the results given on Fig. 5d the variation of the pulse interval above 30 s does not have any influence on the hydrogen removal. It is worth noting that the pulse train with pulse interval of 60 s was conducted before one with pulse interval of 30 s. There was no $H_2$ wall loading before and between the described pulse trains explaining why the outgassing peaks of the first pulse train are higher. The pulse interval of 30 s for a pulse train with discharge length of 1.5 s is sufficient to significantly pump down fuelling gas (hydrogen) and light impurities released during each helium discharge performance, subsequently, the effect of release products accumulation is not significant during the execution of He discharge sequences. The heavy impurity accumulation can be compensated in the post – discharge period which is almost enough to remove it from the vacuum vessel by pumping. Thus, pulse trains with pulse interval of 30 s compared to one with pulse interval of 60 s cut in half total time of the discharge sequence to attain a given efficiency.

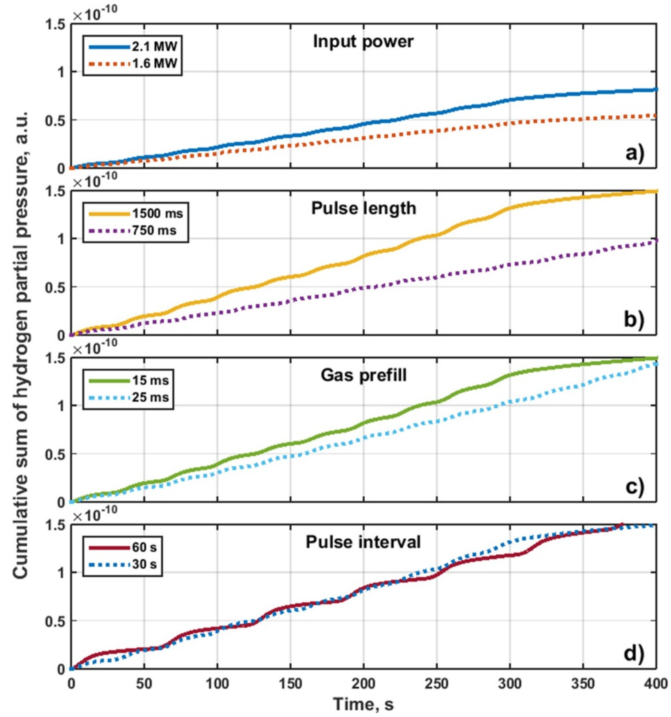


**Fig. 5.** Comparison of pulse train cleaning efficiency represented by removed amount of fuel (integrated QMS hydrogen partial pressure) by variation of:
a) input power, 20170913.50 (2.1 MW) – solid line and 20170913.51 (1.6 MW) – dashed line, for both experiments the following parameters: pulse length is 1.5 s, pulse interval is 30 s, gas prefill is 15 ms.
b) pulse length, 20170919.8 (1500 ms) – solid line and 20170919.9 (750 ms) – dashed line, for both experiments the following parameters: input power is 2100 kW, pulse interval is 30 s, gas prefill is 15 ms.
c) gas prefill, 20170919.8 (15 ms) – solid line and 20170919.10 (25 ms) – dashed line, for both experiments the following parameters: input power is 2100 kW, pulse interval is 30 s, pulse length is 1.5 s.
d) pulse interval, 20170919.6 (60 s) – solid line and 20170919.8 (30 s) – dashed line, for both experiments the following parameters: input power is 2100 kW, pulse length is 1.5 s, gas prefill is 15 ms.

According to the above mentioned studies, optimum scheme for helium pulse train conditioning are pulse length of 1500 ms at a pulse interval no longer than 30 s. The input power for every discharge of a pulse train is ~ 2100 kW. Moreover, based on experimental experience, first 50 ms of each pulse the amount of input power was slightly higher to support discharge break-down. He pre-puff should be done during 15 ms with the constant gas flow of ~ 75 mbar.l/s and 100 ms before each discharge break-down. The developed pulse train with the given parameters was also successfully tested during the high-density hydrogen plasma studies in OP1.2a (20171114.45 and 20171121.39).

Another type of He ECRH – based wall conditioning method which was developed and studied during OP1.2a are so called high energetic "single He recovery discharges", namely long discharges in helium at low density, moderate heating power and with the pulse length up to 10 s. These discharges were carried out as a possible alternative of He pulse trains. A specific advantage lies in possibility to use the discharges as for physics experiments in helium. The typical recovery discharge length was above 2 s and the energy of discharge could reach 30 MJ. The comparative analysis of single recovery discharges application is given on Fig. 6a.

The results show that 10 s 30 MJ He recovery discharges were the

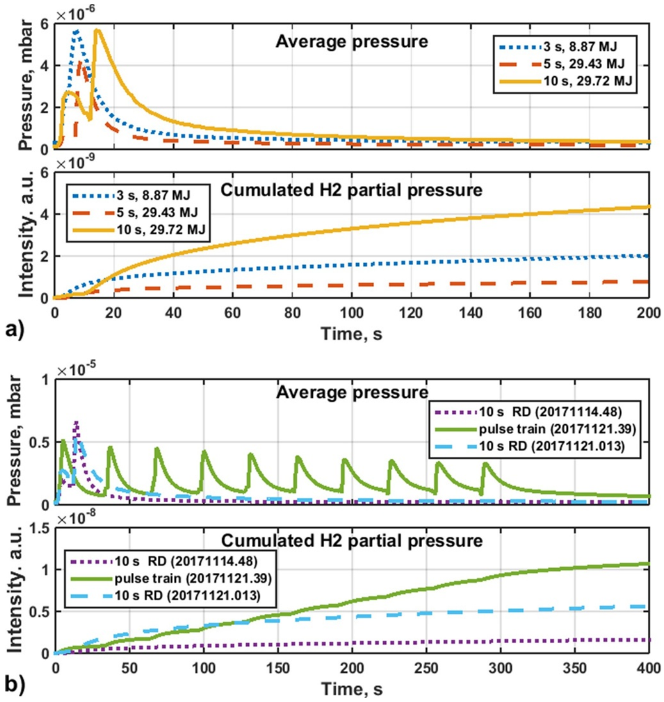


**Fig. 6.** Neutral gas pressure, cumulated hydrogen partial pressure (QMS) for a) 3 s recovery discharge 20171121.33 (dotted line), 5 s recovery discharge 20171109.53 (dashed line) and 10 s recovery discharge 20171121.13 (solid line). b) 10 s recovery discharge 20171114.48 (dotted line), pulse train 20171121.39 (solid line) and 20171121.13 (dashed line).

most suitable for fast wall desaturation and control of impurity release among all other type of single recovery discharges explored in OP1.2a. Moreover, the recovery efficiency, in case of single recovery discharges, does not directly correlate with discharge duration and input energy. For example, as it is shown on Fig. 6a, the discharge with the length of 5 s and input energy of ~ 29 MJ removes less hydrogen than a 3 s recovery discharge with three times less input energy. That means that removal rates can also depend on other parameters such as wall loading and the PFC temperature. This finding indicates further investigations to be conducted.

The last step of He ECRH wall conditioning investigation and improvement process is to compare the optimized pulse trains and single recovery discharges. To do the proper comparison these ECRH wall conditioning methods has been performed in the similar operational conditions. The removal of two 10 s He recovery discharges and one He pulse train is shown on Fig. 6b. The single 10 s He recovery discharges at 3 MW of power remove only 50–75% of hydrogen compared to the pulse train. Long high energetic discharges require up to 8 min of waiting for ECRH gyrotrons to cool down. Due to the high probability of a radiative collapse during this type of recovery discharges and, sometimes, insufficient result the discharge is often repeated one or two times. These facts lead to the increase of total time for preparation, execution and post – discharge procedures which can exceed time spent on pulse train performance by factor of 1.5–2. Thus, considering He pulse train with the pulse length of 1.5 s, duty cycle of 30 s, input power of 2.1 MW and gas prefill of 15 ms is the most effective ECRH wall conditioning tool which has been developed in OP1.2a.

## 4. Conclusion

In the first divertor campaign on W7-X different wall conditioning techniques were found to be optimized by a systematic change of characterizing parameters. Based on the presented studies, the following set of methods and settings appear to lead to improved wall conditions. GDC and ECRH wall conditioning was routinely used during the first divertor campaign (OP1.2a).

GDC remained the main wall conditioning technique for W7-X in the absence of a magnetic field after vessel vents, impurity events and wall saturation by fuel due to its simplicity and high efficiency. $H_2$ – GDC was weekly conducted to sustain the satisfactory amount of impurities outgassing. This type of wall conditioning has been optimized such that the maximum possible cleaning efficiency was achieved at neutral gas pressure of $4.5 \times 10^{-3}$ mbar and anode current of 1.5 A. The fast break-down scheme for $H_2$ – GDC has been developed to minimize possible oscillations of current-voltage characteristics, thereby, to avoid the potential occurrence of arcing and the subsequent damage of vacuum vessel components. He – GDC has been chosen as the daily tool to desaturate the PFC from hydrogen prior to the beginning of plasma operation. The duration of optimized He – GDC did not exceed 20 min that was enough to reach good wall conditions level. The following parameters, i.e. neutral gas pressure of $3.8 \times 10^{-3}$ mbar, anode current of 1 A, have been defined as being most suitable. He-GDC was first ignited in hydrogen to have robust discharge break-down, whereafter, the working gas was changed to helium. That allowed to reduce the effect of PFC erosion.

When GDC was not applicable, in the presence of magnetic field, He ECRH wall conditioning methods were used as a tool to recover density control throughout the experimental days. This tool was applied to recover wall conditions after radiative collapses or to sustain a certain level of wall loading by hydrogen to prevent radiative collapse. Two types of methods have been investigated. The first type is He pulse trains which is sequence of 10–20 equidistant short pulses with the same operational parameters. The results of pulse train optimization show that the best performance can be achieved using the following parameters: pulse length of 1.5 s, interval of 30 s between discharges, input power of 2.1 MW, gas prefill during 15 ms and 100 ms before each discharge break-down. Series of 10 discharges were chosen as optimal pulse trains for saving of experimental time. Other investigated methods were single recovery discharges, namely long high – energetic ECRH discharges in He. Initially, this type of wall conditioning was considered as a fast alternative of pulse trains due to relatively long performance time of last ones. It has been found that the most efficient discharges for wall desaturation from hydrogen were 30 MJ discharges with the duration of 10 s. But, the probability of radiative collapse during the optimized single recovery discharges remained high. Thus, to achieve the reliable cleaning results sometimes it was necessary to use 2 or 3 single discharges in a row. The efficiency comparison of both types of He ECRH wall conditioning method shows that high-energetic 10 s single recovery discharges remove only 50–75% of hydrogen compared to the pulse train. Moreover, total operation time for pulse train is usually 1.5–2 times less than for series of few single recovery discharges.

Nevertheless, the further optimization of all mentioned wall conditioning methods is strongly required to create an optimum set of wall conditioning techniques which is routinely used operations to achieve good wall conditions in a short period of time.

## Declaration of interest

None.

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