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# Wall conditioning and density control in the TJ-II stellarator

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**Abstract**

Helium glow discharge cleaning (GDC) at room temperature, applied during the overnight periods between experimental days, has been used as standard method of wall conditioning in the TJ-II stellarator during the initial operation with ECRH plasmas in an all stainless steel scenario. However, the density control at medium and high power injection (more than 300 kW) becomes difficult due to the contribution of He implanted on the wall during GDC and desorbed by plasma discharges. He desorption rates of $\sim 4 \times 10^{10}$ cm$^{-3}$ ms$^{-1}$ have been estimated from residual gas analyser (RGA) postpulse measurements. In order to overcome this effect, an Ar GDC of a duration of 30 min prior to the TJ-II operation, and after the overnight He GDC have been applied in the last campaign. The Ar GDC removes of the order of $10^{21}$ He atoms (about one monolayer) from the walls allowing a good control of the plasma density by means of external gas puffing. Values of $Z_{\mathrm{eff}} \sim 2.0$–$2.5$ in $H_2$ plasmas and mass spectra measurements of thermal desorption show that the contribution of Ar implanted to the plasma fuelling is not important. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Wall conditioning; Stellarator

## 1. Introduction

During the first campaign of TJ-II stellarator ($R = 1.5$ m, $B = 0.95$ T and average minor radius a $< 0.23$ m) He and $H_2$ plasmas have been produced and heated only by ECRH at 53.2 GHz by means of two independent heating lines with injected power up to 600 kW (300 kW per line) [1]. The typical bean shape plasmas of TJ-II are limited by the region of the vacuum vessel surrounding the central coil system, acting as toroidal belt limiter [2] or, alternatively, by two mobile poloidal limiters [3]. Up to now only stainless steel components have been exposed to the plasma. Due to the close coupling of the vacuum vessel and the plasma periphery and the small volume of the TJ-II plasmas (less than 1.4 m$^3$) in relation with the great vacuum vessel area, the desorbed impurities during the discharge have a significant influence in the behaviour of the plasma [2]. The density has an higher limit fixed by the ECRH cut-off ($ne(0) = 1.75 \times 10^{13}$ cm$^{-3}$), and a lower limit fixed by desorbed impurities, depending on the injected power. The difference between both of them becomes critical when the maximum microwave power is injected. In consequence, from the beginning of TJ-II operation the most important problem was to obtain an accurate control of the density mainly with the maximum injected power. Another different obstacle in the control of TJ-II discharges is the production of runaway electrons during the ramp-up of the current in the external coils before the ECRH discharge [4]. These fast electrons absorb part of the ECRH injected power affecting the plasma start-up and producing a lack of the reproducibility in the behaviour of the discharge. Their production, detected by a strong increase of the hard X-ray emission, was found to be dependent on the base pressure in the vacuum vessel and on the composition of the residual vacuum. The wall conditioning procedures used in TJ-II in these first campaigns were selected with the aim to overcome these troubles.

## 2. TJ-II vacuum vessel and experimental setup

The TJ-II vacuum vessel, all stainless steel, has been described in detail in previous works [5]. The vessel

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volume is 6 m$^3$ and the total inner area about 75 m$^2$. The vacuum system [6] yields an effective pumping speed of $\approx$4000 l s$^{-1}$ at the vessel and the pressure reaches a value of about $1.0 \times 10^{-7}$ mbar before the bakeout. The analysis of residual gases under high vacuum conditions is carried out with a residual gas analyser (RGA) installed directly in the TJ-II vacuum vessel with a heated, high conductance connection. Another RGA, differentially pumped and connected to the vessel through a low conductance hole and pipe setup allows us to analyse the evolution of gas species produced during the conditioning discharge and the postpulse measurements. Both, the mass spectrometer and the sampling systems are heated to 150°C during the measurements. All the systems are absolutely calibrated for different gases.

In the beginning of 1999 experimental campaign the vacuum vessel was baked at 150°C in a thermal cycle lasting 30 h. The baking was carried out by current induction by applying AC current to the toroidal field coils and using additional electrical heaters in ports and appendages. The expected removal of part of the residual water by the baking, confirmed by the RGA, led to a decrease of the total base pressure, which achieved values in the order of $5 \times 10^{-8}$ mbar. Good conditions were preserved even after the vessel has been pressurised (dry N$_2$) for diagnostic maintenance. Only one baking cycle has been carried out up to now. This is due to the present vacuum conditions, apparently dominated by an external air leak related to the mechanical stress produced during the baking of the chamber. Besides, the residual water can be reduced by means of the He glow discharge cleaning as described below.

## 3. Helium glow discharge cleaning

The initial procedure of wall conditioning during 1998 and 1999 campaigns was He glow discharge cleaning (GDC) at room temperature during overnight periods between operation days [1,2]. In summary, a dc-discharge (300 V, 4 μA cm$^{-2}$) is sustained between two L-shape, fixed, stainless steel anodes and the vacuum vessel acting as cathode. The pressure of working gas is kept constant in the range of $5 \times 10^{-3}$ mbar, under active pumping (2400 l s$^{-1}$), using a feedback gas injection system.

With the exception of the first runs [2], no apparent evolution of CO, CO$_2$ and H$_2$O associated with the conditioning procedure was observed. Even after an atmospheric vent the values of released CO and CO$_2$ were near an order of magnitude smaller than those obtained during the first GDC runs of the TJ-II operation. The main effects of overnight He GDC under these conditions were: (a) to remove the hydrogen implanted on the walls by plasma discharge and (b) to produce an activated surface with a typical wall pumping behaviour. The last effect is observed by the decrease of the residual pressure about 10–20% after the He GDC. Also, the RGA placed directly in the TJ-II vacuum chamber shows a strong decrease of masses 18 and 32. The recovery time of water and oxygen after the He GDC was found to be dependent on the number of GDC cycles previous and the TJ-II shots, increasing as the experimental campaign progressed. Fig. 1 shows the time dependence of the ratio between RGA signals $m/e = 18$ and $m/e = 28$ after an overnight He GDC during three experimental campaigns. This ratio indicates the relation between the residual water and the residual leak in the TJ-II vacuum vessel as the signal of mass 28 remains constant along the campaign. In the first experimental campaign, without baking of the vacuum chamber, the high initial value of the ratio mass 18/mass 28 was reached in a few hours after the He GDC. In the other two campaigns after the baking, the activated wall condition lasted several days after He GDC, showing an increase of the recovery time as the campaign progresses.

The improvement of the base pressure achieved by decreasing the residual water (baking of the chamber followed by He GDC) had an important effect over the reproducibility of the TJ-II discharges. This is due to the suppression of sources of electrons than can be accelerated during the rise of the current in the magnetic coils. The fast electrons produce a non-controllable start-up of the plasma discharge and an strong hard X-ray emission perturbing several plasma diagnostics [4]. A correlation between this X-ray emission and the residual pressure of the vacuum chamber has been found during different TJ-II experimental campaigns. The presence of high values of hydrogenic species in the residual vacuum (e.g., H$_2$O) increases the production of fast electrons in comparison with the presence of other species (e.g., He). As a consequence of that, all the attempts of wall conditioning by means of H$_2$ GDC, typically applied to all metal devices [7], produced series of non-controlled

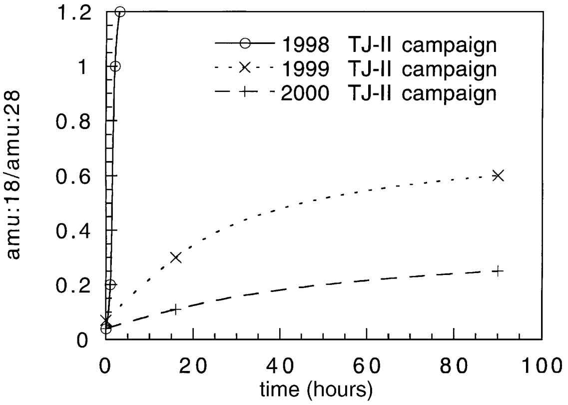

Fig. 1. Evolution of the ratio mass 18/mass 28 after an overnight He GDC during three experimental campaigns of TJ-II.

plasmas with high X-ray emission at the start-up. Besides the $H_2$ GD showed to be unstable in the range of pressures used for the conditioning of TJ-II. No attempts to carry out $H_2$ GDC with hot walls (more efficient for water removing [8]) have been performed yet.

## 4. Density control after He GDC

The main trouble arising from the He GDC procedure is the lack of the particle control due to the plasma fueling by He implanted on the wall and removed during the discharge. Fig. 2 shows the evolution of some significant plasma parameters during the ECRH pulse at 300 kW. The discharge is fueled by an initial $H_2$ prefill pulse (about 50 ms before the shot of the gyrotron) and no additional gas puffing was injected during the discharge. As can be seen from the Fig. 2, the density increases continuously during the discharge, whereas the other parameters show a more constant behaviour. The discharge belongs to a series of discharges, at constant ECRH power, starting just after the He GDC conditioning. The first discharges of the series presented a more pronounced raise of the density reaching the value corresponding to the ECRH cut-off. As the series progresses the slope of the density raise decreases, the ECRH cut-off is not reached and the power absorption is sustained along the discharge, as can be seen in Fig. 2. However, a constant density, as expected without external gas puffing, is only reached at the end of the day (after ≈20 discharges). Moreover, under these conditions the control of the density with $H_2$ external puffing during the discharge was not possible, because the plasma response to the puffing could not be controlled.

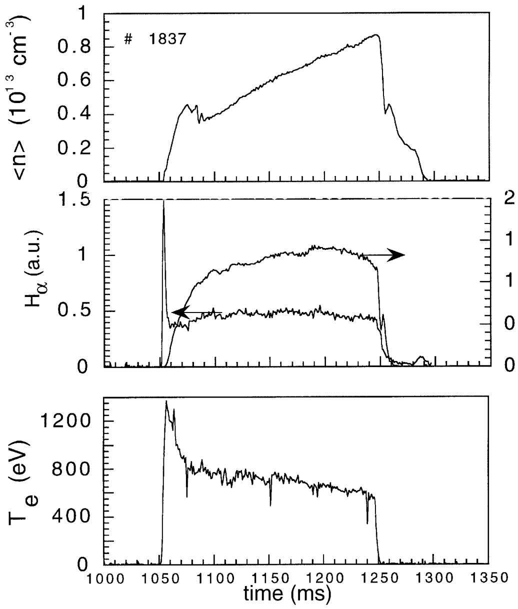

Fig. 2. Time evolution of plasma parameters in a TJ-II discharge ($P_{ECRH}$ = 300 kW, ⟨a⟩ ~22 cm) after He GDC.

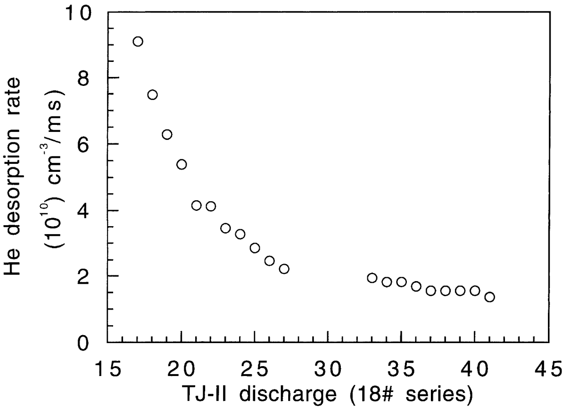

Fig. 3. Evolution of the plasma induced Helium desorption during a sequence of TJ-II discharges along an experimental day. The helium is implanted on the walls during the overnight He GDC.

The continuous raise of the electron density during the discharge with constant Hα emission implies the presence of impurities as fuelling species. As the evolution of carbon and oxygen does not follow the same tendency, another species must be involved in the behaviour of the density. The release of helium, that has been implanted in the metal walls during the overnight GDC, has been studied by means of the RGA in the plasma postpulse. The desorption rate of He produced in the previous series of discharges is showed in Fig. 3. The maximum He desorption rate yields on the order of $10^{19}$ particles in a 200 ms plasma and corresponds to those discharges, the first ones of the sequence, reaching the cut-off density value. These values are in good agreement with a simple particle

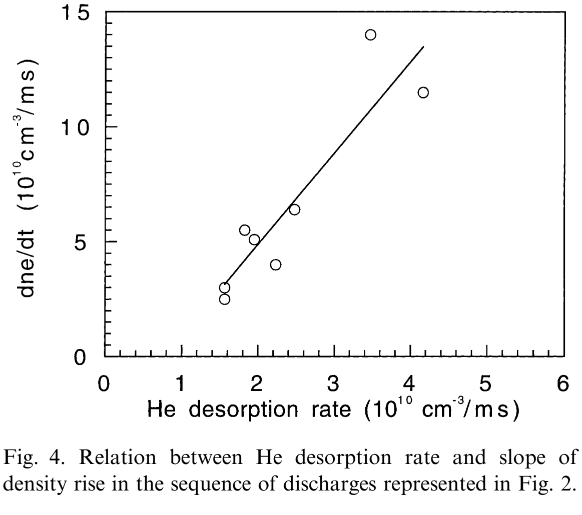

Fig. 4. Relation between He desorption rate and slope of density rise in the sequence of discharges represented in Fig. 2.

balance for the TJ-II standard configuration (plasma volume $\approx$1 m$^3$). Fig. 4 shows the proportionality between the slope of density raise and the He desorption rate, indicating that the raise of density is due to He release at least to a fraction of 50%. This value must be considered as a lower limit because the data from RGA postpulse measures can be underestimated by the influence of TJ-II magnetic fields in the RGA.

## 5. Wall conditioning by Ar GDC

As the intensive He GDC seems to be necessary in TJ-II in order to have reproducible discharges, a method to remove the implanted He from the walls before the operation is required. Since the end of 1999 campaign, a short ($<$30 min) glow discharge in Ar has been applied every day before the TJ-II operation and after the overnight He GDC. According to the mass spectrometer data, the Ar GDC removes on the order of $10^{21}$ atoms of He from the walls (equivalent to one monolayer in the TJ-II vacuum chamber). The effect of Ar GDC over the control of the discharge is shown in Fig. 5. The figure shows the evolution of central density and H$\alpha$ signal in discharges with different gas fueling and an ECRH power of 500 kW. Comparing with the results from Fig. 2, the better control of the discharge with only $H_2$ prefill pulse is clear in spite of the higher injected power in the experiment of Fig. 5. The depletion of helium from the surface is verified by measurements of He desorption by plasma discharge in the afterglow plasma. The values obtained were a factor ~50–100 lower than those obtained after He GDC and no evolution similar to that shown in Fig. 3 was observed.

The constant density during the discharge with only $H_2$ prefill pulse must be produced by the contribution of desorbed species to the plasma, as the H recycling after GDC is lower than 1. The contribution of Ar to the hot plasma is expected to be low because the much lower probability of ion implantation in the metal of Ar ions comparing with the He. This is evident from the analysis of the residual vacuum between discharges after Ar GDC. The RGA data show a contribution of mass 40 about a factor 50 lower than those corresponding to mass 4 and mass 2. Also the desorption of Ar by plasma discharges, measured by RGA in the TJ-II postpulse, renders values of desorption rate on the order of $10^9$ cm$^{-3}$ ms$^{-1}$, which are one order of magnitude lower than those obtained for He.

In order to understand the contribution of desorbed species to the plasma, a thermal desorption experiment was carried out. Gyrotron 100 ms pulses were shot directly on the TJ-II vacuum vessel before the first plasma discharge and the desorbed species were analysed by the RGA. The results show that hydrogen is the main desorbed species, followed by helium ($\approx$10% of hydrogen) and CO (mass 28) in a smaller amount. The amount of desorbed Ar was below the experimental limit and a measurement of desorbed water was not possible, probably due to conductance problems in the system or to the strong wall pumping by the activated wall. Assuming that the desorption by plasma interaction produces a similar relationship between different species, the contribution of desorbed Ar to the hot plasma seems to be minimal. Values of $Z_{\mathrm{eff}}$ ~2.0–2.5 estimated for $H_2$ TJ-II plasmas from X-ray measurements support the assumption of a low contribution of Ar to the plasma fuelling.

Finally, the density could be controlled by external gas puffing after the conditioning by Ar GDC. Fig. 5 shows a discharge, at 500 kW of ECRH power, fueled by an external $H_2$ puffing injected during the discharge. The gas puffing was programmed such than the central density was sustained below the cut-off value.

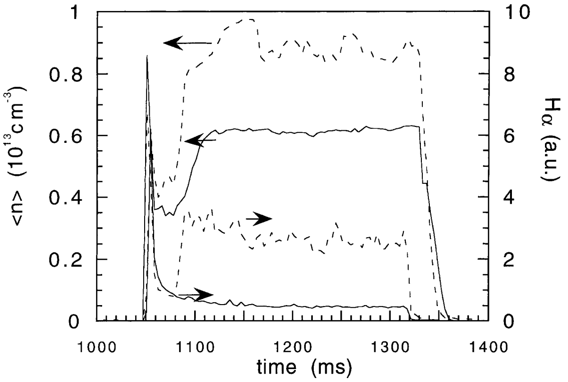

Fig. 5. Electron density and H$\alpha$ signal in TJ-II discharges after Ar GDC. $P_{\mathrm{ECRH}} = 500$ kW, $\langle a \rangle$ ~22 cm. (–) discharge fueled with $H_2$ prefill pulse. (- - - -) external gas puffing injected during the discharge.

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