Development of wall conditioning and tritium removal techniques in TEXTOR for ITER and future fusion devices

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Abstract. Wall conditioning and tritium removal are discussed for ITER for standard glow discharge (GDC) which can operate only without toroidal magnetic field and for RF conditioning plasmas (ion cyclotron wall conditioning, ICWC) which can operate with the magnetic field on. ICWC plasmas have been produced in a wide range of parameters in TEXTOR using the conventional ICRF antennas and analyzed with respect to the wall cleaning efficiency. Various gases have been tested for wall conditioning and tritium removal such as hydrogen, helium, oxygen, nitrogen, ammonium and mixtures thereof. ICWC conditioning plasmas have been optimized based on proper gas mixtures and/or overlaying a small vertical magnetic field to the toroidal field. A simple 0-D plasma model has been developed which defines the parameter space needed for ICWC wall conditioning in ITER.

1. Introduction

Like in all tokamaks, conditioning of the plasma-facing surfaces in ITER must be possible, in particular before operation, after openings, vents, major leaks or major disruptions. This is particularly needed since the plasma start-up up in ITER must be done at low specific ohmic heating power which requires ECRH (or ICRF) assisted ramp up scenarios. In general, conditioning in ITER is focused towards to major goals: (i) limitation of the release of hydrogen and impurities during the sensitive plasma start-up period and (ii) contributing to the control/limitation of the tritium (T) inventory in the surface layers of the plasma facing components. The standard inter-shot, overnight, weekend wall conditioning method used in present devices is glow discharge cleaning (GDC) in connection with regular wall coatings, mainly boronisation (Be evaporation in JET, Li evaporation in some devices). GDC is not applicable under the presence of the magnetic field in ITER which will be maintained for several weeks at a time. Present guidelines specify that the TF magnets can be cycled to zero 1000 times during the life of the machine at which occasion standard GDC wall treatment can be applied [1].

An additional method of inter shot, daily or weekend wall conditioning with magnetic field on is therefore needed to support plasma start up and to contribute to the control of the long term tritium retention. Special ICRF- sustained cleaning discharges (Ion Cyclotron Wall Conditioning, ICWC) have been produced in TEXTOR and elsewhere using the conventional ICRF antennas (without modifications in the hardware) and analysed with respect to optimise the plasma parameters and the conditioning efficiency. In previous experiments, the removal of carbon by oxidation with molecular oxygen has been tested in TEXTOR at wall temperatures between 560–620K.

For the plasma start-up, GDC (with B_T off) or ICWC in He/H_2 mixtures are suitable. To control the fuel retention by inter shot/night/weekend wall treatment, reactive gases must be used (such as oxygen, ammonium and others) in order to maximise the removal efficiency. Reactive gases de-condition the PFC surfaces for subsequent plasma start up, requiring thus the combined application of ICWC for fuel removal followed by wall conditioning. In TEXTOR, ICWC in pure and oxygen/helium mixtures has been analysed and first experiments with nitrogen- and ammonium hydrogen mixtures have been done.

2. Wall conditioning for plasma start up

The amount of fuel particles in thermonuclear plasmas typically corresponds only to about a few monolayers on the surface of the entire wall at which scale technical surfaces are contaminated with adsorbents, like water, hydrocarbons or oxide layers. With plasma impact, these impurities are released (by sputtering, ion induced desorption, electron stimulated desorption, photodesorption or thermal evaporation), penetrate into the plasma increasing thereby the radiation loss which eventually lead to a radiative collapse or other instabilities in the plasma start up phase. After successful plasma start, plasma operation clean the plasma wetted surfaces, transporting the impurities to low flux/ shadowed areas or, for volatile species, to the external pumps. The plasma wetted areas are chemically very active to re-absorb volatile impurities in between plasma pulses which enter the torus via external leaks or from the finite vapour pressure of species adsorbed (like water) on low flux/ shadowed areas, contaminating the next plasma start up again. Disruptions can also release impurities (H_2O, CO, C_xH_y) from remote areas (by heating, particle or photon impact) which can also re-adsorb on the plasma wetted areas leading to start up difficulties in the following plasma pulse, explaining the need for wall conditioning after major disruptions. The adsorption of impurities on plasma cleaned surfaces has been analysed in TEXTOR following the partial pressures of impurities under the presence of external air leaks or by injection small amounts of O_2 in between discharges or overnight. As seen in Fig 1, the O_2 partial pressure which establish in TEXTOR due to an air leak drops drastically after a plasma pulse after which it recovers slowly with time.

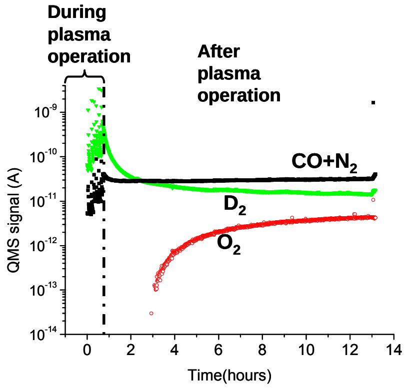

Fig 1: *Residual QMS signal of mass 4 (D_2), mass 28 ($CO+N_2$) and M32 (mainly O_2) after plasma operation in TEXTOR under conditions with an air leak of about 2×10^{-4} mbarl/sec*

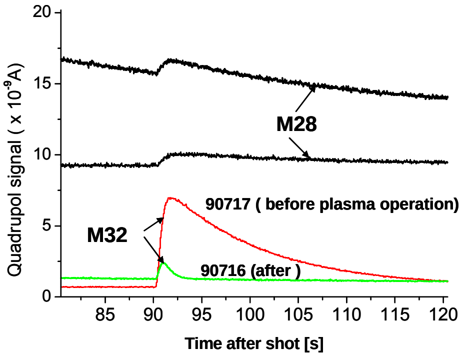

Fig 2: *Time evolution of mass 32 (mainly O_2) and mass 28 ($CO+N_2$) residual pressure signal after injection of the same amount of O_2 in TEXTOR torus before (90716) and after the first plasma pulse (90717) in the morning*

The drop is due to adsorption of O_2 on surfaces cleaned by plasma operation pulse and the recovery of the O_2 pressure corresponds to the saturation of the surface adsorption sites. Fig 2 shows the same behaviour by tracing the mass spectroscopic signals of O_2 (M32) and CO (M28) after injection a small (but same) amount of O_2 just before the plasma operation in the morning and just after the first pulse. About 90% of the injected O of about 2×10^{17} O-atoms is adsorbed on the walls on activated surface sites created by the plasma operation.

To support plasma start up, GDC in He and H_2 is commonly used which releases the non-volatile impurities by sputtering and ion induced desorption transporting them to surface areas shadowed from GDC or by forming volatile products which are pumped out. During wall conditioning, impurity release and re-adsorption proceed simultaneously (as in normal plasma discharges), to clean the surfaces the impurity release on the plasma wetted areas must overcome the re-deposition. By changing conditions of the conditioning plasmas (e.g. by changing from GDC to ICWC plasmas) additional impurities from remote areas can be released which can shift the balance on the plasma wetted areas to deposition which appears then at first as plasma contamination rather then cleaning.

2.1. GDC wall treatment for tritium control

In a low Z wall environment as foreseen for ITER (C, Be) the majority of fuel retention is by co-deposition of T with eroded wall material transported from erosion areas to deposition areas. Control of fuel retention by wall conditioning must reduce the retention on these deposition areas, while removal of the fuel retention from erosion areas will not contribute since the removed fuel will be filled up again in subsequent plasma shots. Fuel control by GDC must therefore erode the deposits thereby releasing the incorporated fuel. The direct ion induced desorption of fuel by GDC (isotope exchange) is restricted to a shallow surface layer. To remove fuel from carbon deposits, reactive gases must be used such as oxygen which is favourable since it erodes carbon with an erosion yield of about unity, more then 10 times faster than erosion by hydrogen plasma. Since oxygen also de-conditions the plasma facing surfaces, other reactive gases are presently under investigation such as N_2, NH_3, see below.
The erosion of carbon deposits by oxygen glow has been analysed in TEXTOR [2] by GDC in pure O_2 and He/O_2 mixtures using 4 GDC antennas at a current of 6A acting on the TEXTOR wall area of about 35 m^2 . After an initial trapping of the injected oxygen, the particle balance showed a nearly completely (> 70%) transformation of O_2 to CO and CO_2 which were pumped out removing thereby about 1.3 gC/hour. This must be compared with a carbon deposition rate of typically about 1 gC/operation day (≈ 200sec of plasma) in TEXTOR. In ITER, however, the duty cycle will increase (≈ 30 times) requiring long GDC in oxygen to remove the (carbon) deposits formed during operation to which the time needed for wall cleaning to recover plasma operation must be added. Plasma recovery was achieved in this case by long (weekend) GDC in H_2 after which plasma operation recovered but with a significant higher O contamination, see e.g. Fig 3. So far, not enough (systematic) studies of wall cleaning for plasma recovery after oxygen treatment have been done in TEXTOR since boronisation was commonly used to quickly and successfully recover operation. No damage to any component inside TEXTOR has been recognised.

GDC cannot be applied in the presence of magnetic fields, as demonstrated in Fig 4 which shows the relative GDC current in dependence of an externally applied magnetic field on different positions in a toroidal vacuum chamber with a GDC operating from one anode fixed to one position (simulating tokamak conditions). Already at about 4mT, the GDC current at positions away from the antenna vanishes while the current concentrates more and more to the vicinity of the anode. This restricts GDC wall conditioning in ITER to the periods with B_T off and calls urgently for development of alternative conditioning methods which can be applied in the presence of magnetic fields.

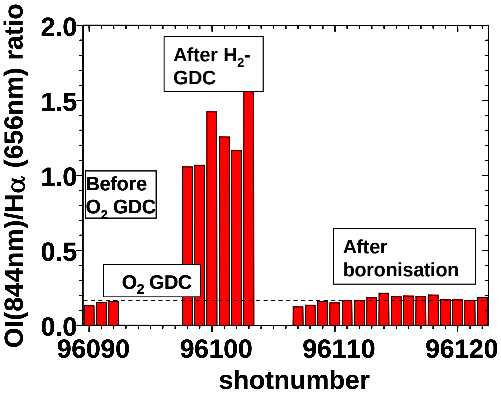

Fig 3: *OI/Hα signal ratio in ohmic shots before O_2 GDC , after H_2 GDC cleaning and after boronisation*

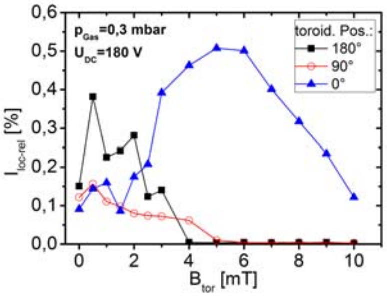

Fig 4: *Local GDC current in a toroidal geometry with one fixed GDC antenna depending on external magnetic field*

2.2. Fuel removal by oxygen gas injection

GDC acts mainly on the plasma facing surfaces, quite uniformly over the plasma wetted wall area but does not penetrate into gaps or much to remote areas. Oxidation by molecular has thus been tested in TEXTOR which has been demonstrated in several laboratory experiments to remove redeposited carbon layers by forming CO and CO_2 leading to the release of hydrogen. Significant oxidation rates could be achieved in the temperature range between about 520 and 750 K, depending on the type of the carbon film or the carbon deposit [3]. At these temperatures, the carbon bulk material is not significantly attacked by the molecular oxygen. The main advantage is that all surfaces including hidden areas and gaps can be reached.

Molecular oxygen O_2 was injected in TEXTOR [4] up to a total pressure between 0.007 and 0.32 mbar at wall temperatures ranging from 520 to 650 K. After an initial higher reaction rate the formation of CO and CO_2 was about 2.5×10^{18} CO+CO_2/s at 0.25 mbar O_2. This corresponds to a removal of 0.08 gC/hour, a factor of 15 below that during oxygen GDC as described above. In the pressure range investigated the reaction to CO was about linear in pressure whereas the formation rate of CO_2 increases with increasing pressure. With higher filling pressure the removal can be further increased but lab data show a tendency of saturation with pressure above about 100 mbar [5].

A significant part of the injected oxygen was adsorbed on the TEXTOR walls, at the highest pressure of 0.32 mbar about 20 % of the injected oxygen within 2 h.

3. Ion cyclotron wall conditioning plasmas (ICWC)

3.1 Plasma production

ICWC plasma production and characterization is described in detail in [6]. ICWC plasmas have been reliably produced in TEXTOR at any Bt (0.20–2.24 T) in various gases and a wide rage of gas pressures ($\sim10^{-3}$–10^{-1} Pa) at the RF generator frequency of 29 MHz. The RF plasma density is in the range of $\approx5\times10^{16}$– 3×10^{18} m^{-3} and about proportional to the injected RF power. Typical Te values are 3–30 eV and the ionization degree is low ≤ 0.1. The antenna coupling (fraction of the generator power coupled by RF plasma) is typically only about ≈20–40%. Spectroscopy shows a quite uniform toroidal plasma distribution but significant poloidal inhomogeniteis. R&D has concentrated and is ongoing in TEXTOR to improve the antenna coupling and the plasma homogeneity with the following main results:

- Lower B_T or higher frequency operation [7]
- ECRF pre-ionization/assistance for the ICRF plasma production [8]
- Mode conversion in plasmas with two ion species [7,9]
- Antenna “magnetic tilting” towards $B_{tot}=B_T+B_V$ by superposing an additional vertical magnetic field $B_V<<B_T$ [10].

3.2. ICWC in H_2, D_2 and He

For the RF frequency of 29 MHz and a B_T of 2.25 T the location of the ion cyclotron resonances for protons and deuterons, $\omega=\omega_{cH}=2\omega_{cD}$, is inside the deuterium/hydrogen plasma at the low field antenna side at r=0.32 m of TEXTOR. There are no such resonances inside the plasmas at low (1.3 T) and high (2.5 T) B_T. However, the total amount of particles outgassed during the overall conditioning cycle of an ICWC pulse (≥140 s) showed an unexpectedly weak B_T-dependence in the range 1.3 T–2.5 T. The obtained result was probably related to weak ion cyclotron absorption in the presence of high hydrogen concentration (≥45%) at which the RF power was mainly absorbed by electrons (>80%) [9].

To analyze and quantify the wall cleaning efficiency, the TEXTOR walls have been preloaded in a D_2+Ar GDC for 5 min and afterwards three identical ICWC discharges were performed to release Ar and D (by isotope exchange with H forming HD). At high B_T (2.25 T in Textor) best results have been obtained in He/H_2 mixtures (mode conversion scenario) at a RF power of about 100 kW. A continuous He flow of 8.5×10^{20} He/sec was injected and overlaid by a H_2 puff during the ICWC pulse feedback controlled with the neutral pressure at the antenna box (6×10^{-4} mbar) to avoid the arcing in the antenna boxes resulting in the injection of about 1.2×10^{21} H-atoms in 5 sec. This resulted in overall removal rate of about 1.5×10^{19} D atoms/sec from the previously D-saturated TEXTOR walls. This absolute removal rate is about comparable with that obtained in D_2-GDC for a hydrogen saturated wall, which however operates at lower power (few kW) and has a better spatial homogeneity. The wall area affected in He+H_2 mixture at 2.25 T compared with that at 0.2 T (at which the affected wall area was assumed to be more homogeneous) was about 50%, while the temporal decay of the hydrogen and impurity release (Ar) in consecutive shots indicated an affected wall area of about 25%. More analysis and optimization of the spatial homogeneity of such ICWC plasmas is subject of further research in TEXTOR.

3.3 ICWC in reactive gases

3.3.1. Oxygen

Reliable and reproducible ICWC pulses with a duration of 3–8 sec were produced at B_T=2.3 T in a continuous He flow of 2×10^{20} He/s to which molecular oxygen (~4×10^{20} molecules/shot) was puffed during a period of ~4 s reaching typical parameters of n_e= 4 – $7\cdot10^{16}$ cm^{-3} and $T_e\approx$5–7 eV with an RF power of 50–90 kW from one or two antennas at 29 MHz. At first oxygen is absorbed in the walls onto walls but after a few ICWC pulses the wall is saturated. Practically no O_2 could by detected the QMS during the ICWC pulse but mainly CO and CO_2, confirmed by spectroscopy showing the presence of intense CO and CO^+ molecular bands and atomic lines *OI* (777nm, 845nm) but no molecular oxygen bands. A strong adsorption of CO and CO_2 on the walls was also seen when the oxygen puffing was stopped prior the ICRF plasma and the CO, CO_2 partial pressures dropped with a time constant much faster (1.5 – 2 s) and depending on the input ICRF power than the vacuum pump out time (16 s). A gas balance shows that up to 70% of injected oxygen was converted into CO and CO_2 in proportion of typically 4:1 totally about 4.5×10^{20} molecules per ICWC pulse (8 s plasma + 135 s pumping out) with most of the CO and CO_2 released after the ICRF plasma. The removal rate increased with higher O_2 injection but was restricted by the maximum neutral pressure in the antennae box (about 5×10^{-4} mbar) for arc-free operation.

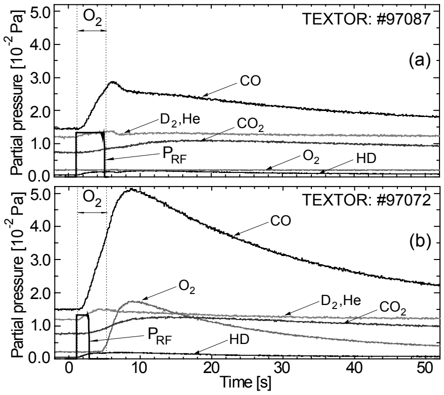

Fig.: 5 *ICRF O-wall treatment for conditions with puffing 0_2 only during the ICWC plasma (a) and after the ICWC pulse (b)*

This maximum pressure limits the CO production and thus C removal rate while GDC can operate at higher gas pressures. This has been partly improved by puffing O_2 after the ICWC pulse with increasing injection rate showing a continuous conversion to CO but also a rising O_2 neutral pressure. This is demonstrated in Fig 5.

3.3.1. Nitrogen

A D_2 continuous flow of 9.6×10^{20} D_2/sec was used and feedback controlled N_2 gas was overlaid during the ICRF plasma. Even at the highest N_2 injection ($\approx10^{21}$ N_2 molecules per pulse) which would rise the pressure to about 2×10^{-3} mbar without plasma the total pressure remained low ($< 2\times10^{-4}$ mbar). The overall Ar release was weak and the HD removal rate was a factor of about 6 smaller than in $He+H_2$. The strong pressure drop during ICRF plasma in D_2+N_2 must result from the retention of nitrogen in the walls which must be stronger than that of O_2. No saturation of N retention in the TEXTOR walls has been observed in these experiments, opposite to the behavior of oxygen. Nitrogen can be stored in metallic surfaces, in graphite but may also react with boron layers remained after boronisations leading to the formation stable boron nitride compounds.

3.3.1. Ammonia

Similarly, ICWC plasmas in Ammonia were created by feedback controlled NH_3 puffing (6–8×10^{20} NH_3 /pulse) in plasmas created by continuous He (8×10^{20} He/sec) or D_2 (10^{21} D_2/sec) flows [11]. The total pressure increased when ammonia gas was injected and the removed amount of Ar atoms was comparable with that of the $He+H_2$. The maximum of the removal rates was reached at 17 s ($He+NH_3$) and 12 s (D_2+NH_3) after the ignition of the discharge. A good spatial homogeneity was estimated of about 100% and 70% for $He+NH_3$ and D_2+NH_3 respectively. It is speculated that the increase of the wall area was due to the effect of neutral ammonia radicals impinging more homogeneously on the TEXTOR wall than the ICWC plasma ions, but more work is needed to confirm this hypothesis. Fig 6 compares the Ar removal rates for different ICWC gas mixtures in TEXTOR.

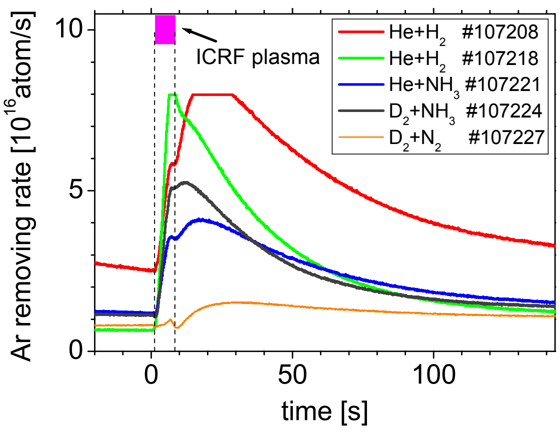

Fig 6: *Ar removal rate for ICWC plasma application in different gas mixtures in TEXTOR. The TEXTOR walls were preloaded before each ICWC plasma with Ar in a GDC plasma in Ar/D_2*

4. ICWC application in ITER

The ITER case ($\bar{a}_{pl}\approx 2.6$ m, R_0=6.2 m, B_T=5.3 T) has been modeled using a recently developed 0-D plasma code based on the electron collisional ionization with the updated reaction rates [6]. For the starting phase of wall conditioning in ITER, a high density case has been analysed predicting a weakly ionized ($\gamma_i\approx 1.4\%$) plasma at low temperature ($T_e\approx 1$ eV) and low density ($n_e\approx 4\times 10^{11}$ cm^{-3}) with a low coupled power with the electrons ($P_{RF\text{-}e}\approx 850$ kW). With a coupling efficiency of about 50%, a relatively low power at the RF generator ($P_{RF\text{-}G}\approx 1.7$ MW) will be necessary. At reduced gas pressure ($p_{H2}\approx 2\times 10^{-2}$ Pa) and increased RF power ($P_{RF\text{-}e}\approx 3.4$ MW, $P_{RF\text{-}G}\approx 6.8$ MW) an increased ionization degree, $\gamma_i\approx 16\%$ is obtained. This regime would need a power density of about 3.5 MW in good agreement with a simple extrapolation from TEXTOR. This type of plasma leads also to a higher re-ionisation of released impurities which would reduce the removal efficiency which must be weighted, however, with the increase in wall fluxes at higher ionisation degree.

5. Summary

GDC is a well proven technique to support plasma start up after openings or special events (like leaks) and is important for ITER. It can, however, not be applied with magnetic field on. To support plasma start up for standard conditions or more regular events like disruptions, and to contribute to the long term T inventory control, ICRF wall conditioning (ICWC) plasmas has been developed which could reliably be produced in reactive gas mixtures in different mixtures of hydrogen, deuterium, oxygen, nitrogen or ammonia in TEXTOR and elsewhere. A quite uniform toroidal plasma homogeneity has been found with, however, stronger poloidal asymmetries. In order to optimize the homogeneity, operation at mode conversion in RF plasmas with two ion species and/or overlaying a small vertical magnetic field has been proved to be effective, but more work is needed in this area. For standard wall cleaning, a mixture of H_2/He is recommended while, to optimize the removal of carbon and tritium, a mixture of O_2 with He is the most effective scenario. The efficiency is mainly limited by the maximum pressure in the antenna box. Nitrogen-hydrogen and nitrogen-deuterium gas mixtures were found to be ineffective for wall cleaning under the wall conditions in TEXTOR due to strong nitrogen consumption by the wall. Ammonia containing gas mixtures were applied for the first time in TEXTOR with no drawback of the injected ammonia for the tokamak operation. A helium-ammonia gas mixture showed a better uniformity than ICWC in the helium-hydrogen mixtures.

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