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Ion cyclotron wall conditioning in reactive gases on TEXTOR

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ABSTRACT

The influence of working gas on the performance of Ion Cyclotron Wall Conditioning (ICWC) has been studied in the TEXTOR tokamak. Several reactive gases (H_2, D_2, O_2, N_2, NH_3) and their mixtures with He were tried and primary results about their efficiency to clean the wall from impurities and to release the retained fuel have been obtained. The experiments have demonstrated in general that low temperature plasmas produced in these gas mixtures by a conventional ion cyclotron heating system are suitable for wall cleaning. For comparison of the cleaning efficiency of different gas mixtures (except O_2), the TEXTOR wall was preloaded with Ar and D in a glow discharge. The release of Ar atoms due to ICWC has shown a sequential reduction in series of ICWC plasma pulses. This reduction was used as a criterion for the cleaning efficiency. For the fist time ammonia has been tested for the wall conditioning in a tokamak and demonstrated Ar and D cleaning efficiencies similar to the He/H_2 mixtures.

1. Introduction

Wall conditioning has been demonstrated to be an important procedure for today's fusion devices to clean the walls from impurities, such as oxygen, carbon, water and hydrocarbons, in order to enable reproducible plasma start up and to reduce plasma dilution and radiation losses. For future devices like ITER, wall conditioning will be essential mainly for plasma start up. The other even more important task in ITER is the control of the tritium inventory, which requires a set of different techniques among which wall conditioning is an important part. GDC is foreseen for ITER [1], however, this technique cannot be routinely used due to the presence of permanent strong toroidal magnetic field. An alternative technique, Ion Cyclotron Wall Conditioning (ICWC) has been studied in TEXTOR [2–4] and other tokamaks [5–7]. This method utilizes a standard Ion Cyclotron Range of Frequency (ICRF) heating system to produce weakly ionized plasmas in the presence of the toroidal magnetic field. From the beginning ICWC was done in standard gases (He and D_2) [2–7] but later the more chemically reactive O_2 was applied to increase the removal rate for carbon [8,9]. Reactive gases have the ability to react chemically with impurities or deposits and convert them into volatile products, which can be pumped out from the vacuum chamber. However, reactive gases should not contaminate the wall too strongly or, at least, should be removable from the wall by ICWC in standard gases like helium or deuterium and some residual species should not affect the plasma operation. Apart from oxygen, recent laboratory studies have shown that nitrogen–hydrogen mixtures and ammonia plasma can also effectively remove carbon layers by chemical erosion [10–12]. Nitrogen–hydrogen mixtures were proposed as an alternative working gas for wall conditioning in thermonuclear devices [13] and used for the first time for ICWC on the Uragan-3M torsatron [14].

2. Experimental

ICWC was performed in the TEXTOR tokamak [15], which has a major radius $R = 1.75$ m and a minor radius $a = 0.46$ m with a wall area of about 35 m^2 and a chamber volume of about 16.5 m^3. TEXTOR has a liner which is placed at $r = 0.55$ m made of inconel and covered by a boron layers due to periodic boronisations and also re-deposited carbon in the vicinity of the graphite limiters. The toroidal pump limiter and part of the inner wall are made from graphite and cover approximately 30% of the wall. The standard TEXTOR ICRF heating system consists from two double straps shielded or unshielded antennas, which can be fed each by a 2 MW generator via a transmission line [16,4]. In the ICWC experiments reported here, a generator frequency of 29 MHz with a power of about 50 kW per antenna at a toroidal magnetic field B_T of 2.25–2.3 T was used. Under such magnetic fields only about 50% of the RF power delivered to the antennas was absorbed by ICWC plasmas depending on the gas mixture used. A small vertical

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magnetic field B_V of up to 0.04 T was occasionally applied to improve the vertical homogeneity of ICRF plasma and to increase the area of the plasma interaction with the wall. One Quadrupole Mass Spectrometer (QMS) continuously monitored the gas composition in the TEXTOR vacuum chamber with a time resolution about of 10 s and a second one was used to measure the partial pressures of eight selected masses during the plasma pulse with higher time resolution (20 ms). The amount of gas injected into the vacuum chamber was monitored by flow-meters for continues gas flow and by measuring the pressure drop with baratron gauge in a gas pre-volume for short gas pulses. A baratron gauge measured the total pressure in the vacuum chamber with a time resolution of 10 ms. The QMS were calibrated against dry gas injection (without plasma) for the gases used for ICWC. A double Langmuir probe measured the electron temperature and density of the ICRF plasmas. In addition, a compact spectrometer measured plasma emission in a wavelength range of 370–850 nm with a spectral resolution of about 1 nm and a time resolution of about 30 ms along a midplane chord of the torus. Silicon samples coated by amorphous hydrogenated carbon (a-C:D) and boron films placed at the wall (liner) position were used to monitor the effect of the conditioning plasma on the coatings.

3. Results and discussion

Several reactive gases (D_2/H_2, O_2, N_2, NH_3) and its gas mixtures with He or D_2/H_2 have been tested on TEXTOR for ICWC. To compare the cleaning efficiency of ICWC in different gas mixtures, argon and deuterium were implanted into the wall by means of GDC in D_2 + Ar gas mixture prior to each ICWC cycle to be used as the marker gas afterwards. He-GDC with duration of 3 min was applied every time prior to the D_2 + Ar GDC of 5 min duration to improve the reproducibility of the wall conditions. After wall loading three identical ICWC discharges were performed for each gas mixture under the test. Since the amount of Ar released by the ICWC pulse is proportional to the Ar surface concentration prior the pulse, a decay of the Ar release with a pulse number indicates the fraction of Ar that could be possible to remove by the ICWC conditioning. The ICWC discharges were rather inhomogeneous in B_T = 2.3 T and mainly concentrated on the low field side. When B_T = 0.23 T was used, the ICRF plasma filled out the torus volume more homogenously. This discharge was used as a reference for comparison of the wall area accessible for the cleaning in the different gas mixtures.

3.1. ICWC in He + O_2

Wall cleaning with ICWC in oxygen was performed under a continuous He flow of $1.8 \cdot 10^{20}$ H/s (He pressure $\approx 10^{-4}$ mbar before pulse) and about $4 \cdot 10^{20}$ O_2 molecules puffed during the ICRF plasma pulse of about 8 s. The measured plasma parameters near the wall were Te = 5–7 eV and ne = $(4–7) \cdot 10^{10}$ cm^{-3}. In the beginning the injected oxygen was retained totally on the walls but after a few ICWC pulses the wall became saturated as measured by the increase of the total neutral pressure during the oxygen puffing. However, the QMS did not practically detect O_2 but mainly CO and CO_2. This was confirmed by spectroscopy showed the presence of intense CO and CO^+ molecular bands together with atomic lines OI(777 nm) and OI(845 nm) but no molecular oxygen bands were detected. If the oxygen puffing was stopped during the ICRF plasma, the pressure dropped with a time constant of 1.5–2 s depending on the input ICRF power as seen in Fig. 1. This pressure decrease is much faster than that of vacuum pump out time ($\approx$16 s for CO), demonstrating the ionization and decomposition of CO molecules and the absorption of the products on the walls.

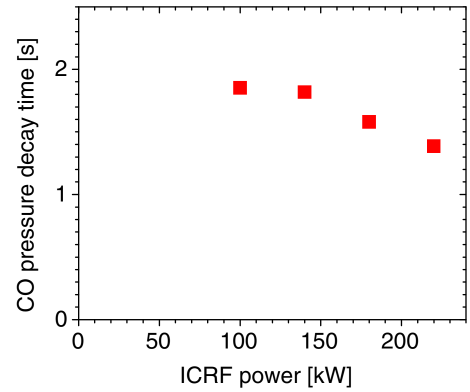

Fig. 1. Decay time of CO partial pressure after the stop of O_2 puffing into the plasma versus total ICRF power.

The gas balance shows that up to 70% of the injected oxygen is converted into CO and CO_2 in proportion of about 3:1 and pumped out, about $4.5 \cdot 10^{20}$ molecules per ICWC pulse (8 s plasma + 135 s pumping out). In this pulse like mode, most of CO and CO_2 are released after the ICRF plasma. The removal rate increased with increasing gas puff rate but was restricted by the maximum neutral pressure in antennae box (about 10^{-3} mbar) allowed for arc-free operation. This shows that an increased pumping speed would allow more oxygen throughput and carbon removal. No systematic studies on plasma restart have been performed in this experiment. The restart of normal plasma operation of the tokamak was achieved after D_2-GDC over a long period of time followed by He-GDC and boronisation.

3.2. ICWC in D_2

To remove oxygen retained in the wall ICWC in pure D_2 was used. About 10^{21} D_2 molecules were puffed during 8 s into ICRF plasma in addition to a constant D_2 flow (18 sccm, $8.1 \cdot 10^{18}$ D_2/s, and pressure $2.3 \cdot 10^{-4}$ mbar). With ignition of ICRF plasma, the gas is consumed and stored in the walls as seen on the drop of the total pressure which reach a maximum after the plasma termination, with H_2 and HD the main components of the released gas. In the sequence of the repetitive ICRF pulses, the outgassed amount of the CO decreased from pulse to pulse as shown in Fig. 2. About 16% of CO molecules were removed per ICWC pulse from the wall. The total amount of CO molecules, which could be removed, is about $4 \cdot 10^{20}$ that corresponds to one monolayer if the molecules would be homogeneously distributed over the whole wall area.

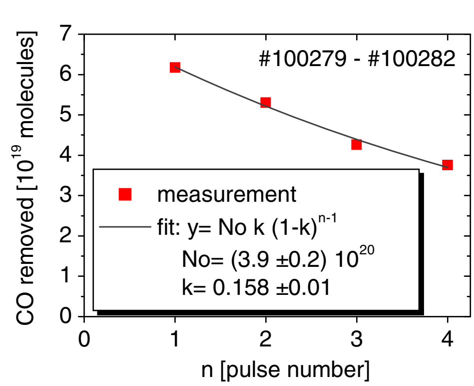

Fig. 2. Number of CO molecules removed from TEXTOR in series of ICWC pulses in D_2. The fit shows the amount of CO molecules that could be removed and fraction of CO removed by single ICWC pulse.

3.3. ICWC in He + H_2

In addition to continuous He flow of 35 sccm (pressure $3.7 \cdot 10^{-4}$ mbar), H_2 was puffed during the ICWC pulse (7 s) and feedback controlled with the neutral pressure at the TEXTOR chamber. The feedback kept the total neutral pressure at about $6 \cdot 10^{-4}$ mbar to avoid the arcing in the antenna boxes. About $6 \cdot 10^{20}$ H_2 molecules were injected during 5 s puffing.. The Ar started to release from the wall during H_2 puffing into the ICRF plasma and continued to release with a lower rate after the termination of the plasma, as shown in Fig. 3. About 50% of Ar atoms were removed per ICWC pulse from the wall area accessible for the cleaning. The removal rate of HD and D_2 molecules during the ICRF plasma was about $6 \cdot 10^{18}$ HD/s and $4 \cdot 10^{18}$ D_2/s, respectively, as shown in Fig. 4. This removal rate for HD is comparable with the removal rate in D_2-GDC for a hydrogen saturated wall. The wall area affected in He + H_2 mixture was about 50% with respect to the reference discharge.

3.4. ICWC in H_2 + N_2, D_2 + N_2

To test the cleaning capability of nitrogen, a D_2 continuous flow of 40 sccm ($1.8 \cdot 10^{19}$ D_2/s) was used and feedback controlled N_2 gas puffing was applied during the ICRF plasma. The total neutral pressure strongly dropped during the ICRF plasma and did not exceed $2 \cdot 10^{-4}$ mbar, as shown in Fig. 5, even when $9.5 \cdot 10^{20}$ N_2 molecules were puffed during 5 s, which should lead to a pressure increase up to $2 \cdot 10^{-3}$ mbar without plasma. A similar behaviour was also observed with H_2 + N_2 gas mixture. However, the overall Ar release was weaker as one can seen in Fig. 3. Also 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. It s know that nitrogen can be stored in metallic surfaces and in graphite but also chemical reaction of nitrogen atoms and ions with boron layers remained after boronisations leading to the formation stable boron nitride compound may be important. In spite that most of injected nitrogen was retained in the wall, plasma restart was possible after only a few ICWC discharges in deuterium, albeit with an increased level of nitrogen and high radiation losses in the plasma.

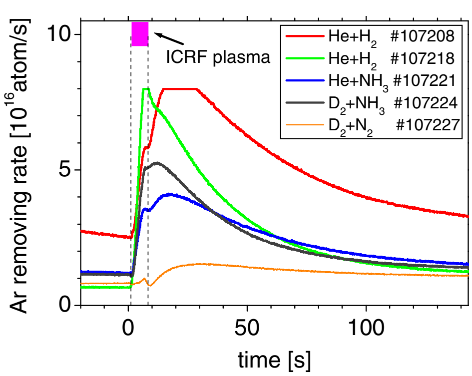

Fig. 3. Argon removal rates during ICWC in different gas mixtures. #107218 is the reference ICWC pulse at low magnetic field B_T = 0.23 T.

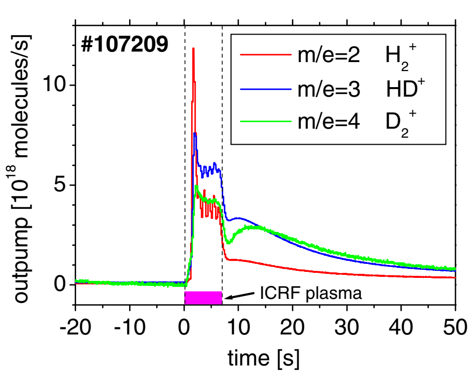

Fig. 4. Hydrogen isotopes removal rates during ICWC in He + H_2 gas mixture.

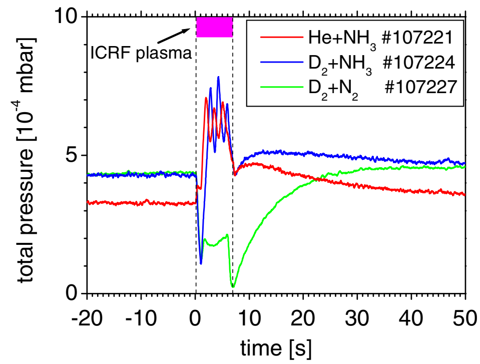

Fig. 5. Evolution of the total pressure during ICWC in He + NH_3, D_2 + NH_3 and D_2 + N_2 gas mixtures.

3.5. ICWC in He + NH_3, D_2 + NH_3

ICWC plasmas in ammonia were created by feedback controlled NH_3 puffing during ICRF plasmas in continuous He (35 sccm) or D_2 (40 sccm) flows. About $6 \cdot 10^{20}$ NH_3 molecules were injected during 4 s puffing in He + NH_3 and about $8 \cdot 10^{20}$ NH_3 molecules – during 5 s puffing in D_2 + NH_3. Contrary to the case of N_2 puffing the total pressure increased when ammonia gas was injected, see Fig. 5. The removed amount of Ar atoms was comparable with that of the He + H_2 gas mixture but the removal rates were higher during ICRF plasma especially for D_2 + NH_3. The wall area accessible for the cleaning was about 100% for He + NH_3 and 70% for D_2 + NH_3 case. The plasma appeared to be still inhomogeneous like in the case of He + H_2, so we assume that the increase of the wall area accessible for the cleaning was rather due to neutral ammonia radicals, than due to plasma ions. The fraction of Ar atoms removed per ICWC pulse in He + NH_3 and D_2 + NH_3 was about 40% and 50%, respectively. The removal rates of HD and D_2 in He + NH_3 were the same as for the He + H_2 gas mixture. In the case of D_2 + NH_3 the HD removal rate was about 2.5 higher because the presence of the additional deuterium from the gas injection. The intensities of the mass peaks with $m/e = 28$ (N_2^+, CO^+, DCN^+), $m/e = 27$ (HCN^+), $m/e = 18$ (H_2O^+, NH_2D^+), $m/e = 19$ (HDO^+, NHD_2^+) and $m/e = 20$ (D_2O^+, ND_3) are strongly increased during ICWC in ammonia containing gas mixture but was essentially weaker than the intensities of m/e=2 (H_2^+), $m/e = 3$ (HD^+) and $m/e = 4$ (D_2^+).

4. Conclusions

The experiments demonstrated that ICWC plasmas could be reliably produced in different mixtures of hydrogen, deuterium, oxygen, nitrogen or ammonia. A mixture of O_2 with He is the most effective scenario to remove carbon from the wall with an efficiency, which was mainly limited by the maximum pressure in the antenna box. ICWC in deuterium was effective to remove CO and hydrogen via HD isotope formation. Ammonia containing gas mixtures were applied for the first time for wall conditioning in a tokamak. No drawback of the injected ammonia was found for the tokamak operation. A helium–ammonia gas mixture was found to be effective to remove deuterium and showed a better uniformity than ICWC in the helium–hydrogen mixtures. 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. One explanation might be the formation of stable boron nitride compounds but more work is needed to confirm this. Ammonia containing gas mixtures will be further studied in future experiments to evaluate more precisely the efficiency for the carbon removal.

Acknowledgement

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