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New scenarios of ICRF wall conditioning in TEXTOR and ASDEX Upgrade

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Abstract

Inter-machine studies of wall conditioning with the ICRF discharges have been performed in the limiter (TEXTOR) and divertor (ASDEX Upgrade (AUG)) tokamaks in the presence of a toroidal magnetic field ($\geqslant 2$ T) using the conventional ICRF antennas without modifications in hardware. The vessel oxidation treatment by pulsed ICRF discharges in ($He + O_2$)-mixture (TEXTOR) is analyzed in terms of ratios of the RF pulse length to the O_2-puff duration. A successive set of deuterium and helium ICRF discharges was developed for *post-oxidation* wall cleaning and analyzed in the light of TEXTOR recovery to the normal plasma operation. A new scenario of ICRF wall conditioning in ($He + H_2$)-mixture at two frequencies was applied in AUG and compared with the standard glow discharge in terms of outgassing efficiency. Modeling of the absorbed RF power was done to clear up a role of the H_2 concentration in the homogeneity of ICRF plasmas and the generation of high-energy ions.

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1. Introduction

Long term retention of tritium (T) fuel in the surface or bulk material of plasma facing components is one of the major problems for nuclear

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fusion reactor, since the amount of in-vessel retained T is safety limited [1]. The dominant retention mechanism is T co-deposition with carbon due to the formation of amorphous tritiated carbon layers, a-C:T, which can grow continuously on the plasma facing sides and also on the hidden remote areas. *Thus, the removal of T from the a-C:T layers may require the removal of co-deposited layers themselves.* The oxidation of carbon layers by plasma-assisted technique is considered as one of the most promising techniques [2]. The plasma production technique compatible with the presence of high toroidal magnetic field and based on absorption of the radio-frequency (RF) power in the ion cyclotron range of frequencies (ICRF) was successfully tested during the O-treatment experiments on tokamaks HT-7 [3] and TEXTOR [4]. However, the results revealed the main drawback for operation of the present-day ICRF antennas with O: limitation of the maximal neutral pressure in the antenna box to certain values allowed for the antenna safe operation in the presence of RF voltages ($p_{tot} < p_{lim} \approx 1 \times 10^{-1}$ Pa). The other big concern was related to tokamak recovery to normal operation after the O-treatment. So far, this process is not well documented and needs systematic study. We report here the results on further development of the ICRF discharge conditioning (ICRF-DC) in oxygen (TEXTOR), the inter-machine (TEXTOR, AUG) studies of ICRF wall cleaning in D_2 and in $(He + H_2)$-mixtures and their effect on the tokamak plasma recovery after the O-treatment (TEXTOR).

2. Oxidation treatment with ICRF discharges

ICRF discharges in a pulsed-mode operation (RF pulse length $t_{RF} \approx 3$–8 s) were successfully initiated in TEXTOR with the toroidal magnetic field $B_T = 2.3$ T in a continuous He flow within the pressure range of about $(1–2) \times 10^{-2}$ Pa, to which molecular oxygen ($\sim 4 \times 10^{20}$ molecules/shot) was puffed during a period of $\sim$4 s starting from 0.1 s after the ICRF ignition. Reliable and reproducible generation of the ICRF $(He + O_2)$-plasmas with typical parameters $n_e \approx 1.3 \times 10^{17}\ m^{-3}$ and $T_e \approx 5.5$ eV (Fig. 1) were achieved by coupling the RF power $P_{RF} \approx 50$–90 kW from one or two ICRF antennas at frequency $f = 29$ MHz.

Two scenarios of ICRF oxidation with different ratios of the RF pulse length to the O_2-puff duration ($t_{RF}/t_{O_2\text{-puff}} \approx 1, t_{RF}/t_{O_2\text{-puff}} \leqslant 0.5$) were tested. In the first scenario, no neutral oxygen could be

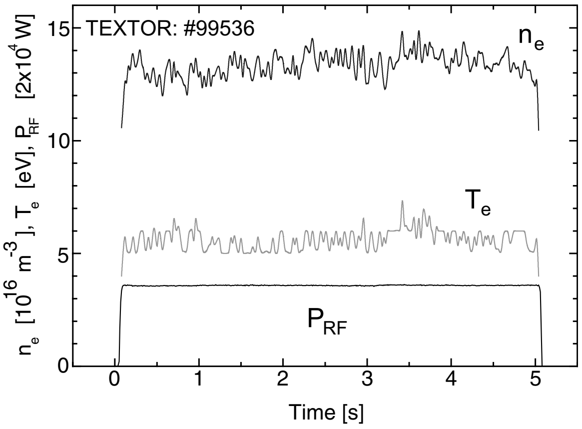

Fig. 1. Time traces of n_e, T_e and RF power in the ICRF $(He + O_2)$-plasma (data from Langmuir probe at the plasma edge, $r = 47.9$ cm).

detected with the differentially pumped quadruple mass spectrometer (QMS) while formation of CO and CO_2 together with the small release of HD and D_2 were observed (Fig. 2(a)). In addition, the partial pressures of CO and CO_2 were observed to be proportional to the O_2 injection rate. This proved that in the presence of ICRF plasmas, the injected O_2-molecules have completely been converted to the atoms through dissociation and to the atomic and molecular ions through ionization. The converted products oxidize the carbonized surfaces efficiently with formation the volatile CO and CO_2

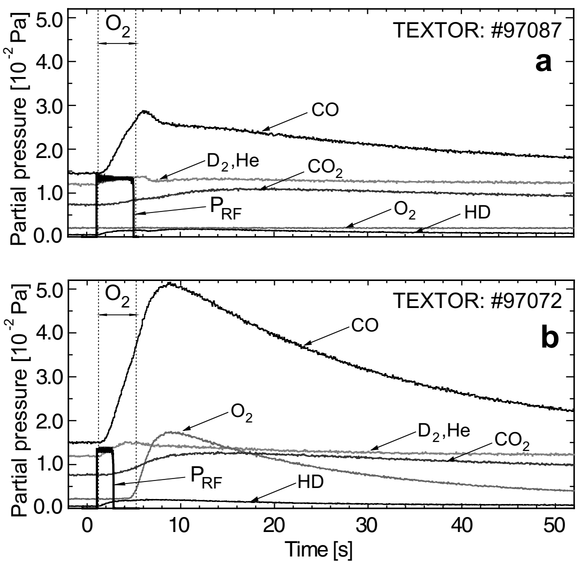

Fig. 2. ICRF O-treatment at longer (a) and shorter (b) RF pulse length compared with the O_2-puff duration.

compounds. The maximum amount of O_2 injected during the RF pulse ($\approx 5.5\times10^{20}$ molecules) was limited by the maximum neutral pressure at the antenna box ($\sim 1\times10^{-1}$ Pa) allowed for non-arcing and low RF power reflection operation of the energized ICRF antenna. As a result, the C exhaust rate was technically limited compared with the O-treatment in glow discharge conditioning (G-DC) operated at higher gas pressures [3,4].

Making the RF pulse shorter ($t_{RF}/t_{O_2\text{-puff}} \leqslant 0.5$) and the O_2 injection rate higher ($\sim$1.4 times) resulted in the partial pressure strong rise for O_2 ($\sim$4 times) and CO ($\sim$2.5 times), both achieved after the termination of the O_2-puff while only minor increase in the CO_2 pressure was noticed (Fig. 2(b)). The dynamical QMS analysis showed that most of the CO and CO_2 products ($\sim$75%) were released after the ICRF pulses in both tested cases due to large difference between the characteristic pumping time ($\sim$30 s) and the RF pulse length. The second tested ICRF scenario (Fig. 2(b)) looks more promising because it allows injecting more O_2 after termination of the RF power. Both, higher pumping speed and higher O_2 injection rate *mainly in-between the RF pulses* at lower RF duty cycle may increase the C removal rate. It will be a subject for further optimization of ICRF-DC.

3. Development of wall cleaning scenarios with ICRF-DC

3.1. ICRF-DC in deuterium

It is well known that the outgassing rate from the wall increases with the impact energy of the ions and their masses [5]. All previously performed ICRF-DC experiments reported observations of the high-energy fluxes of H (up to 60 keV) and of D atoms (up to 25 keV) generated by presence of the ion cyclotron resonance (ICR) for hydrogen, $\omega = \omega_{cH}$, in helium or deuterium RF plasmas [6]. However, the effect of ICR presence or absence on outgassing the walls was not studied properly. Fig. 3 summarizes the first result on the pump-out efficiency of the deuterium RF plasmas in TEXTOR for different masses as a function of the B_T-field at nearly constant coupled RF power (116–125 kW). For the given frequency of RF generator, $f = 29$ MHz, the field $B_T = 2.25$ T corresponded to location of the $\omega = \omega_{cH} = 2\omega_{cD}$ resonance for the protons and deuterons inside the plasma at the LFS (antenna side), $r = +0.32$ m. There were no such resonances inside

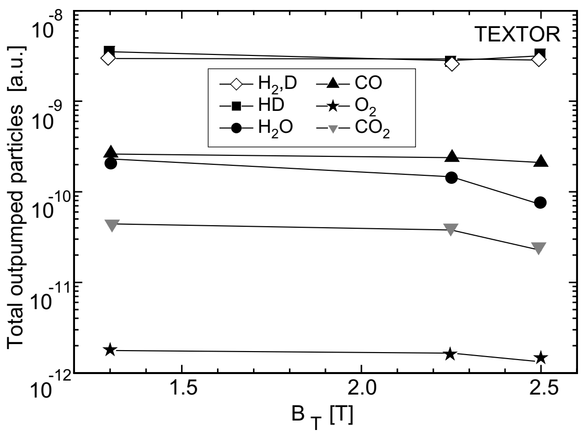

Fig. 3. Effect of outgassing for different gas components in deuterium ICRF-DC vs. the B_T-field.

the plasmas at low (1.3 T) and high (2.5 T) B_T-values. The estimated total amount of the particles outgassed during the conditioning cycle ($\geqslant$140 s) revealed unexpectedly weak B_T-dependence. Further analysis of the obtained result will be done in Section 4 on the base of numerical RF modeling.

3.2. ICRF-DC in helium

Recent ICRF-DC experiments in He in the divertor tokamaks showed a necessity to improve the homogeneity of RF plasmas mainly in the divertor and HFS areas [6]. To solve a problem, an additional injection of hydrogen into the helium plasmas was proposed and realized in JET [6]. The helium/hydrogen RF plasmas ($H_2/(He + H_2) < 0.1$–0.3) in AUG was further extended towards HFS by coupling of the RF power (15–150 kW) from four ICRF antennas operated simultaneously at two different frequencies ($f_{1,2} = 36.5$ MHz and $f_{3,4} = 30.0$ MHz). The pulsed RF discharges with parameters $n_e \sim (3–5)\times10^{17}\ \mathrm{m}^{-3}$, $T_e \sim (3–5)$ eV, $t_{RF} = 5$ s, $B_T = 2.0$–2.4 T and $p_{tot} \approx 4.0\times10^{-2}$ Pa were achieved. In addition, the decrease of the averaged energy of the H and D atoms on rising up the H^+ concentration was observed.

First comparison of ICRF-DC operated in the updated scenario with standard G-DC in the divertor machine was done at *the same energy input per discharge* ($\approx$0.6 MJ). The conditioning cycle consisted from three identical discharges for both conditioning technique. Pre-loading of the walls with the similar amount of Ar was done prior to each conditioning cycle. Argon was used as a marked impurity for better discrimination by QMS. The parameters of conditioning discharges were for ICRF-DC: $P_{RF} \approx 130$ kW, $t_{RF} = 5$ s, $(He + H_2)$-mixture, $p_{tot} \approx 4 \times 10^{-2}$ Pa, $B_T = 2.4$ T and for G-DC: $P_{G\text{-}DC} \approx 2$ kW, $t_{G\text{-}DC} \approx 300$ s, He-gas, $p_{He} \approx 4 \times 10^{-1}$ Pa, $B_T = 0$.

The evolution of the Ar pressure over the conditioning time for both discharges is shown in Fig. 4. For the quasi-steady state, the Ar particle balance equations in the vessel volume and at the wall surface result in the exponential time-decay of the Ar pressure with the decay constant τ: $p_{Ar}(t) = p_{Ar}(0) \times \exp(-t/\tau)$. It suggests that the pressure decay constant is about 56 times smaller in the ICRF-DC case, $\tau_{G\text{-}DC} \approx 56 \cdot \tau_{ICRF\text{-}DC}$. Since the RF conditioning time has been ≈60 times shorter than the G-DC time, one would expect that the similar amount of Ar should be removed during ICRF-DC and G-DC if both discharges clean the same surface area. However, the total amount of removed Ar was found ~50 times smaller in the ICRF-DC case, thus showing inhomogeneous cleaning area. Hence, further optimization of ICRF-DC in AUG is necessary.

3.3. Tokamak plasma recovery after oxidation treatment with ICRF-DC

As was shown by Taylor, hydrogen discharges with low T_e (~3 eV) might efficiently be used for the O-removal from the surfaces [7]. Taking it into account, sequential ICRF wall cleaning in D_2 (11 shots with the averaged coupled power $\bar{P}_{RF} \approx 70$ kW/shot, $p_{D_2} \approx 6 \times 10^{-2}$ Pa, $t_{RF} = 8$ s, $f = 29$ MHz, $B_T = 2.25$ T,) and in He (6 shots with $\bar{P}_{RF} \approx 100$ kW/shot, $p_{He} \approx 4 \times 10^{-2}$ Pa and the same other conditions) was used to remove the residual O from the TEXTOR vessel after the ICRF oxidation experiment. We remind that about 4×10^{21} molecules of O_2 were injected (Section 2). The absorbed O was released mainly in form of the CO and CO_2 molecules. The CO removal efficiency is shown in Fig. 5 as a ratio between amounts of CO removed during D_2 and He ICRF-DC and that one removed in a reference shot before the O-treatment start. Such normalization helps to estimate the number of ICRF-DC needed to achieve a pre-oxidation state of the walls. The removal efficiency of carbon oxide in D_2 RF discharges was much higher than in He (Fig. 5). The probable reason for that was higher electron temperature in the He RF plasmas ($T_{e\text{–}He} \approx 12$ eV) than in the molecular gases (Fig. 1) and the lack of 'chemical nature' in He, both being crucial for the O-removal [7]. However, the cleaning procedure in He was necessary for desaturation of the surface trapped deuterium and controlling the density during the tokamak start-up. The successful tokamak recovery after the ICRF oxidation treatment was achieved by overnight vessel baking followed by 10 disruptive tokamak discharges: three shots with pure Ohmic (OH) power, one OH shot with the ICRF assistance and 6 shots with the NBI assistance. Fig. 6 shows performance of the first successful tokamak shot after the O-treatment compared with a typical first shot of a week. For the first time, the TEXTOR restart was achieved using ICRF-DC alone. However, uncontrolled behavior of the plasma density and still high

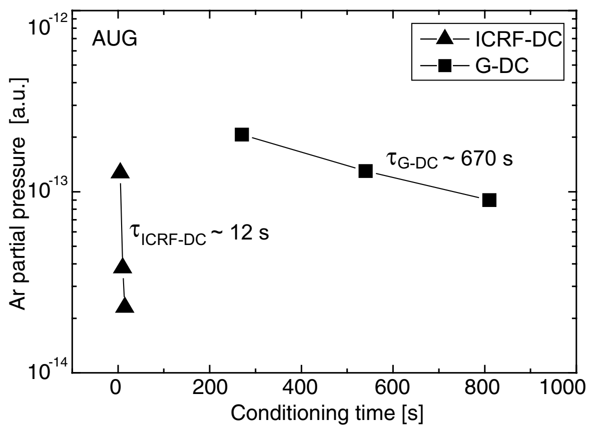

Fig. 4. Evolution of the Ar partial pressure over the conditioning time for ICRF-DC and G-DC performed in AUG at the same energy input ($E \approx 0.6$ MJ).

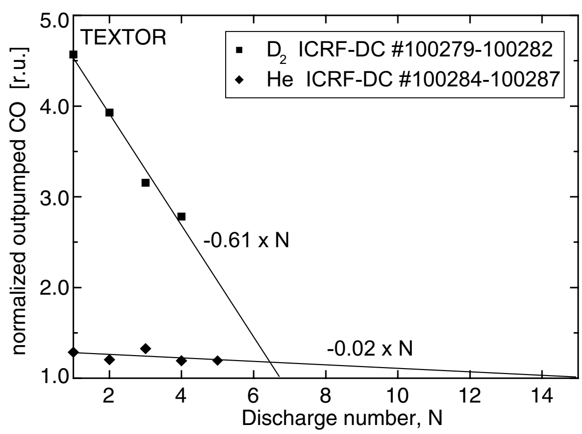

Fig. 5. CO removal efficiency in deuterium and helium RF plasmas normalized to the 'pre-oxidation' condition (#100261).

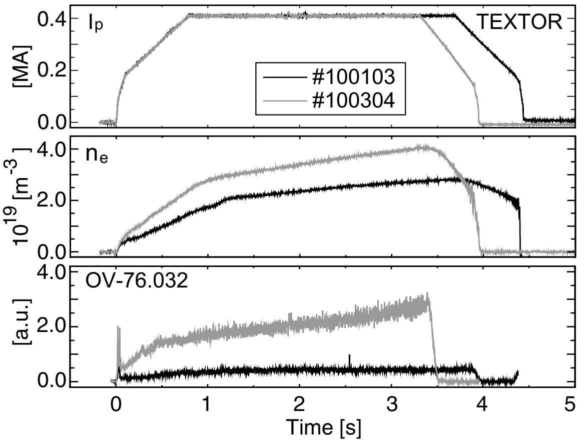

Fig. 6. Time traces of the tokamak plasma parameters before (#100103) and just after (#100304) the O-treatment.

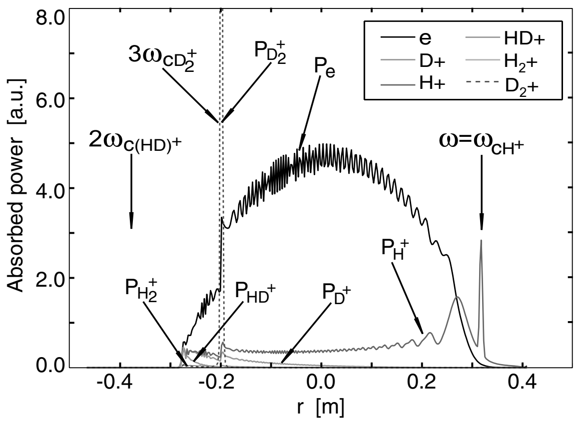

Fig. 7. Calculated RF power deposition in deuterium plasmas at the 'resonant' field $B_T = 2.25$ T.

level of O in the OH-plasmas clearly indicated that the ICRF cleaning procedure should be optimized.

4. Modeling of absorbed RF power

To understand better the result of weak dependence of wall outgassing on B_T (Fig. 3), a calculation of the RF power deposition profiles for the electron and ion plasma species in the frequency range ω to ω_{cH} has been undertaken with the TOMCAT 1D RF code [8]. The following input parameters were used for the calculations: $n_{e0} = 2 \times 10^{17}$ m^{-3}, $T_{e0} = 10$ eV, $T_{i0} = 6$ eV and rather high ratio of $H_\alpha/(H_\alpha + D_\alpha) \approx 0.45$ observed in the present TEXTOR experiments with deuterium RF plasmas. The composition of plasma species was derived from a low temperature plasma model [9]: 44%D^+ + 36%H^+ + 10%$(HD)^+$ + 5.8%H_2^+ + 4.2% D_2^+. Both absorption mechanisms, collisional and non-collisional (ion-cyclotron and electron Landau damping) were included into the calculations. Several main predictions of modeling should be mentioned:

(i) The distribution of the absorbed RF power among the ion and electron species and the absorption areas are strong functions of the H^+ concentration. The dominant and localized near the ICR layer absorption by protons at low H^+ concentrations ($\leqslant$5%) converts to the collisional absorption by electrons at higher H^+ concentrations. The electron absorption area extends from the resonant layer $\omega = \omega_{cH}$ towards HFS on increasing the proton concentration.

(ii) For the conditions of the experiment (Fig. 3, high concentration of the hydrogen released from the walls, $H_\alpha/(H_\alpha + D_\alpha) \approx 0.45$), the principal channel for the RF power absorption is the radially extended *collisional absorption by electrons* from 80% at $B_T = 2.25$ T (Fig. 7) to ≈89% at $B_T = 1.3$ T. The ion species absorb the minor part of the RF power mainly through the ion-cyclotron mechanism with the dominant fraction in protons (weakly varied from ≈13% at $B_T = 2.25$ T to ≈11% at $B_T = 2.5$ T).

The numerical predictions are in the qualitative agreement with the observed weak B_T-variation of the outgassing yield (Fig. 3) and with decrease of the averaged energy of the H and D atoms on rising up the H^+ concentration discovered in AUG. The latter may give an impact on the wall conditioning effect. However, to quantify more conditioning effect, more experiments with variable hydrogen concentration should be done.

5. Conclusions

The inter-machine (TEXTOR, AUG) studies of ICRF wall conditioning aimed on the development of scenarios for tritium retention/removal in fusion reactor resulted in the following:

1. To improve the reliability of the ICRF antenna operation at the very high O_2-pressures ($\geqslant 10^{-1}$ Pa) required for the efficient O-treatment, the new ICRF-DC scenario with higher O_2-injection rate after termination of the RF power was

tested in TEXTOR. The increased output of the O-containing products was achieved in a trouble less regime of the antenna operation.
2. Independently developed *post-oxidation* wall cleaning procedure as a successive set of the ICRF discharges in deuterium (to remove the O-containing products) and in helium (to desaturate the walls with deuterium) resulted in successful TEXTOR recovery to the normal operation.
3. Modeling of the absorbed RF power in the frequency range ω to ω_{cH} predicts strong dependence of the power distribution among the electron and ion plasma species and the area of absorbed power on the H^+ concentration. For wall conditioning applications it means finding a compromise between better radial homogeneity of the ICRF discharge and the generation of more energetic ions/neutrals, which may increase the conditioning effect. New scenario of the ICRF wall conditioning at two frequencies (tested in AUG) is one of such developments that needs further optimization.

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