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Differences of ICR cleanings in He, D_2 and O_2 for deposit removal and hydrogen release in HT-7

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Abstract

The differences in deposit removal and hydrogen release between ICR cleanings with various working gases, He, D_2, O_2, and gas mix of He/O_2, were investigated on hot walls with a temperature of 410–470 K after long deuterium plasma operation in the HT-7 superconducting tokamak. Different mechanism of hydrogen release and deposit removal, such as chemical erosion, physical sputtering, ion induced desorption and isotopes exchange, could explain the difference of ICR cleanings in various gases. The wall conditions, such as deposits and hydrogen retention, would also influence on the efficiency of cleanings for deposit removal and hydrogen release. For each working gas, ICR cleanings with high power and/or high pressure promoted H release. Both the pure O-ICR and D_2-ICR cleanings had a higher removal rate for hydrogen than that in He-ICR cleanings by a factor of 4–6. The O-ICR cleaning had a much higher deposits removal rate than the He-ICR and D_2-ICR cleanings by a factor of a few tens. ICR cleaning techniques in a superconducting tokamak, such as EAST and ITER, should be reasonably arranged, which depend on deposits and hydrogen retention on walls, and requirement of plasma operation and safety.

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1. Introduction

A wide variety of wall conditioning techniques have been developed and applied in tokamaks over past two decades for impurities and hydrogen removal, such as baking [1] and plasma associated cleaning techniques. Plasma associated cleanings could be done, for example, by running low energy conditioning plasmas such as glow discharge cleaning (GDC) [2,3], but various other methods based on RF techniques at electron cyclotron resonance (ECR) [4] and ion cyclotron resonance (ICR) have been employed [5].

The long-term retention of tritium fuel in the surface or bulk of plasma facing materials in fusion devices is one of the major problems in fusion technology. Extrapolation of wall and surface conditioning methods to a device such as ITER is not straightforward. Specific design related features, e.g. superconducting magnets, combined use of

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different wall materials and operational limitations, will preclude or limit the utilization of some of the most extensively used current surface conditioning techniques. The increased duty factor will result in a substantially different conditioning situation than in present tokamaks. It has also been concluded from various investigations that the dominant mechanism for hydrogen retention in tokamak on carbon walls will be co-deposition of eroded carbon with deuterium. The ability to remove tritium from amorphous tritiated carbon layers, a-C:T, co-deposited in the next generation tokamaks, such as ITER, will have an important impact on machine operation [6].

Tritium removal techniques capable of operating in the presence of magnetic fields are desirable due to the permanent toroidal magnetic field in ITER. The permanent presence of toroidal field will preclude GDC cleaning; therefore, ICR conditionings are envisioned for in-between pulse cleaning. High hydrogen removal rates have been reported in ICR experiments in Tore Supra with He and D [5] and Textor with He [7]. In tore supra experiment the C removal rate was estimated to be about $4 \times 10^{22}\ \mathrm{C\ m^{-2}\ h^{-1}}$, which is not enough for application in ITER. Therefore, ICR cleanings with O_2 (O-ICR or O-ECR) were proposed for in-situ deposit removal and H release [8–11].

The theory of plasma production in a tokamak using RF power in the ion cyclotron range of frequency has been investigated [12]. The working gas would be ionized, producing ions with different charges. With suitable parameters, these ions have a resonance absorption layer for the harmonics inside vacuum vessel, depends on the ion charge, the ion mass, and magnetic field. Then, the energetic particles would impact the walls and lead release of gases from the walls. H removal in those discharges occurs via a combination of processes: chemical erosion, physical sputtering, ion induced desorption and isotopes exchange [6]. Etching of deposits and release of hydrogen during ICR cleanings has a rate that could easily be related to power, pressure, reaction rates, and gas-phase kinetics. At a high temperature, thermal release of hydrogen would happen with a little efficiency during ICR cleanings. In the He-ICR cleanings, ion induced desorption by high energy He particles may be the dominant mechanism for hydrogen release. Besides of ion induced desorption, in the D_2-ICR cleanings, hydrogen release could via isotopes exchange too. Especially, because oxygen is active with C and H, H release in O-ICR cleanings happens together with the deposit removal due to chemical erosion in oxidation wall conditioning.

In HT-7, normal techniques, such as baking, GDC and ICR cleanings, were investigated for the impurity removal in last ten years. Especially, RF wall conditioning techniques have been developed with a permanent toroidal magnetic field and are routinely used in HT-7 from 1998 [13,14]. The oxidation wall conditioning for deposit removal and hydrogen release, includes O-ICR [15,16], O-GDC [17] and thermo-oxidation with molecular oxygen [18], have been successfully carried out in the last two years. The highest removal rates of H, D and C-atoms up to 2.64×10^{22}, 7.76×10^{21} and 1.49×10^{22} atoms/hour, respectively, were obtained in 40 kW 9×10^{-2} Pa O-ICR cleaning, corresponding to the removal rate of co-deposits of about 317 nm/day (7.2 g/day for carbon) [15,16]. In the absence of magnetic fields, the O-GDC experiment has produced rapid, controlled co-deposit removal. The O-GDC wall conditioning is an effective method to remove hydrogen and deposits [17]. Oxygen removal from 'clean' walls and from walls with oxygen contamination was investigated with various techniques. On heavy contaminated walls, such as after oxidation experiments, the removal rate of oxygen during He-ICR cleanings depended on oxygen retained on the walls, ICR power and pressure [19]. Deposits modification and hydrogen retention on samples with oxygen plasma exposure were analyzed with SEM and TDS, which will be reported later. After oxygen plasma exposure, the deposits were effectively removed and D_2 retention were reduced by a factor of 2–3. O-ICR plasma has most effective on the deposits removal and hydrogen (deuterium) release on the surface facing the main plasma, whereas O-GDC possibly has an unformed affectivity on board walls.

After 2004, carbon limiters were mounted with about 18% of whole walls in HT-7. To investigate the removal efficiency for hydrogen and impurities on a carbon wall, and to distinguish difference between ICR cleanings with various working gases, He-ICR and D_2-ICR cleanings were specially performed after a long deuterium plasma operation in HT-7 in spring of 2005 experiment. This paper discusses the efficiency of deposit removal and hydrogen release (most on H and not D, due to the difficult to distinguish between He and D_2 by QMS) of ICR cleanings with various gases, such as He, D_2 and O_2. Section 3 will give some new results of He-ICR and D_2-ICR experiments in HT-7 with the new graphite limiter and also briefly reviewed typical results of O-ICR experiments. Sections 4 and 5 give some discussions and a short summary.

2. Setup and procedure

HT-7 is a medium sized superconducting tokamak ($R = 1.22$ m, $a = 27$ cm) [20]. Before 2000, two molybdenum limiters with each about 0.1 m^2 were used. After the beginning of 2004, the plasma was limited with two toroidal limiters and one belt limiter [21], as shown in the Fig. 1. The total plasma facing surface area of the HT-7 graphite limiters was about 2.35 m^2 in 2004 and 1.88 m^2 in 2005. All plasma facing materials for limiters were made from the GBST1308 (1% B, 2.5% Si, 7.5% Ti) doped graphite with about 100 μm SiC coating [22,23]. The rest of the plasma facing surface was formed by the stainless steel liner within a metallic torus with $r = 33$ cm. The effective plasma facing area of limiters and liner was about 12 m^2.

The liner of HT-7 was heated by direct current flow and the limiters were heated by thermal radiation. However, the temperature distribution in HT-7 is very complex, which made the measurement is very difficult. In HT-7, there are total 64 thermocouples in limiter tiles and liners. The big difference would be up to 60 K. During cleanings, temperatures in the limiter tiles and on the liner were measured by 12 thermocouples, which could response normal temperature distribution. In this paper, the differences between various ICR cleanings will be discussed under similar wall temperatures. Even the temperature has difference at various location, it is in a range of 410–470 K. An ICRF antenna, covered in the HT-7 vessel from the top to bottom at high field side with a radius of 33 cm, was utilized for wall conditioning [13,14], as shown in the Fig. 1. The wave frequency of ICR is 30 MHz; the wave power can easily be adjusted. The duty time of ICR wave is 0.3 s on/1.5 s off or 1 s on/2 s off for cleanings. During all experiments, the temperature of the limiter was 402–425 K and that of the liners was 435–470 K. ICR cleanings have been performed in presence of permanent toroidal magnetic field (1.5–2 T). The samples with apparent deposits, cut from doped graphite tiles of HT-7 toroidal limiter after one HT-7 campaign, were exposed to ICR plasmas.

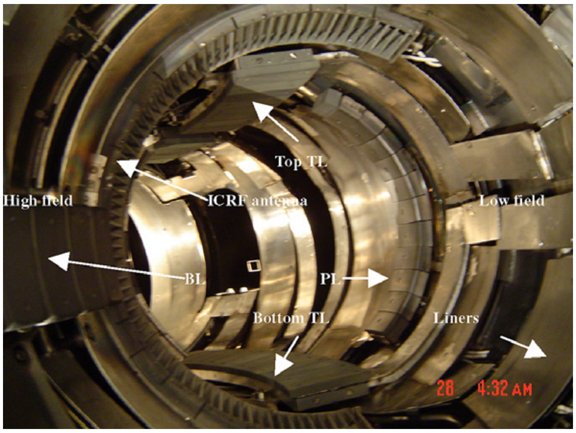

Fig. 1. Set up limiters and ICRF antenna in HT-7 (TL: Toroidal limier; PL: Poloidal limiter; BL: belt limiter).

3. Results

3.1. Partial pressure during ICR cleanings

Fig. 2 shows typical evolution of partial pressure (P.P) of molecules in HT-7 vessel during 20 kW 1.9×10^{-2} Pa He-ICR and D_2-ICR cleanings. At the start of both the He-ICRF and D_2-ICRF cleanings, P.P of H_2 and HD increased whereas that of most oxides, such as H_2O, HDO, CO and CO_2, decreased. This indicates that both He-ICR and D_2-ICR cleaning were effective for hydrogen release. P.P of most oxides deceased possibly means that, on 'clean' walls with carbon limiters, both He-ICR and D_2-ICR cleanings would induce oxygen retention but not removal, which concluded in Ref. [19]. During the He-ICR or D_2-ICR cleanings, it can be concluded that carbon layers could not be effectively removed and that the hydrogen was primarily released in the form of H_2. Both P.P of H_2 and HD in D_2-ICR cleaning are much higher than that in He-ICR cleaning, which indicated that the D_2-ICR cleaning has more efficiency for hydrogen release than He-ICR cleaning.

Fig. 3 shows typical evolutions of partial pressure (P.P) of molecules in HT-7 vessel during 20 kW O-ICR and He/O-ICR cleanings with filling oxygen to a pressure of 1.2×10^{-2} Pa in 2005 experiment. At the start of O-ICR cleanings, the P.P of most gases increased fast whereas that of oxygen decreased. The gases with relatively large increasing pressure are H_2O, H_2, CO and HDO, which is much different from the He-ICR and D_2-ICR cleanings.

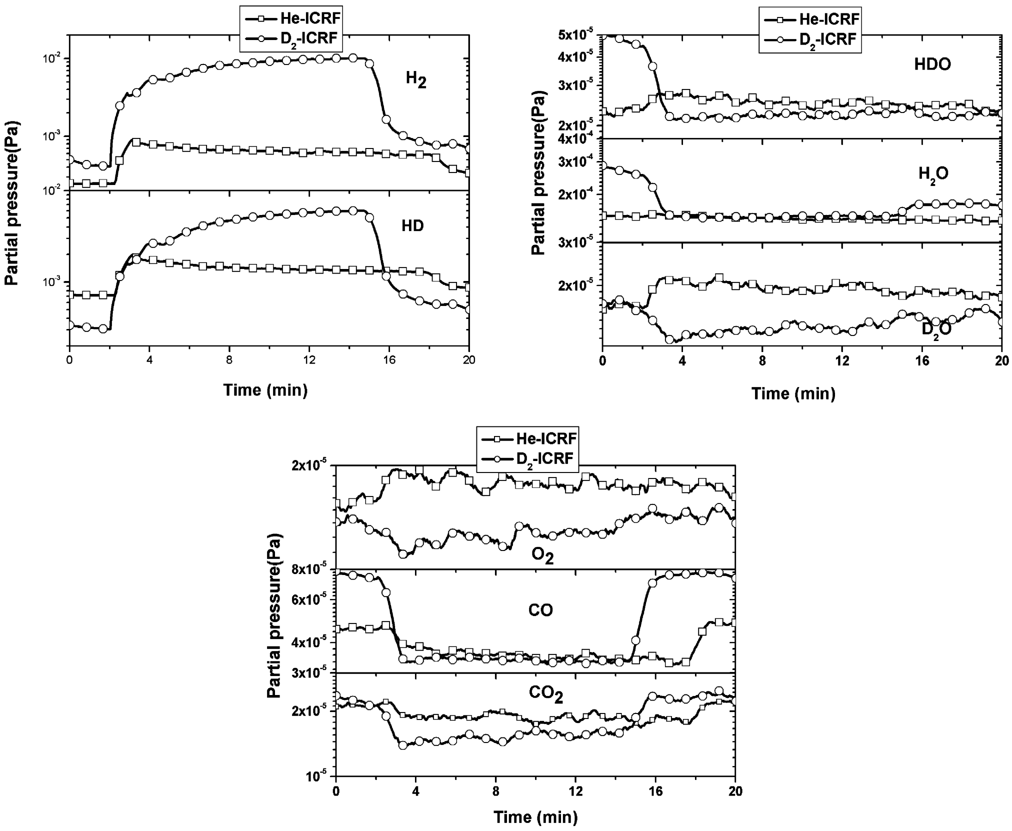

Fig. 2. Time evolutions of the P.P of molecules in 20 kW 1.9×10^{-2} Pa He-ICR and D_2-ICR cleanings.

During O-ICR cleanings, it could be concluded that carbon layers were removed by formation of CO and CO_2 and that the incorporated hydrogen was released primary in the form of water [15,16].

During the 4:1 He/O-ICR experiment [16], the P.P of H_2 increased much lower whereas the P.P of H_2O and HDO increased much higher than that during pure O-ICR experiment, which indicated that He in the O-ICR plasma promote H–O reactions. All P.P of HD, D_2, deuterium oxides and carbon oxides increased much higher than that during pure O-ICR experiment, which means that He in the He/O-ICR plasma also promoted D–O and C–O reactions. In other words, the He/O-ICR cleanings are beneficial for removal of co-deposition because D and C were the main elements in co-deposition after a long term of deuterium plasma operation. The P.P of oxides and O_2 in the He/O-ICR plasma are higher than that during pure O-ICR experiment, which indicted that helium in O-ICR plasma greatly reduced oxygen retention.

Standard He-ICR cleaning was used for oxygen removal after the O-ICR experiment. It was concluded in Ref. [19] that, on heavy contaminated walls, such as after oxidation experiment, the removal rate of oxygen during He-ICR cleanings depended on oxygen retained on the walls, ICR power and pressure. Fig. 4 shows one typical He-ICR cleaning after He/O-ICR in 2005. All detected gases were released very fast as the ICR wave was switched on. No apparent change of the P.P of H_2 indicating that hydrogen release is very low during the cleaning, possibly because most hydrogen had been removed by the He/O-ICR cleanings. The P.P of oxides went down during the cleaning, especially H_2O, an indication that the oxygen content in the volume or from the wall, decreased step by step. Due to high oxygen content or absorption of carbon oxides on walls, carbon was also removed in the form of CO and CO_2, which is much different from He-ICR cleaning on 'clean' walls after long plasma operation as previously indicated in Fig. 2.

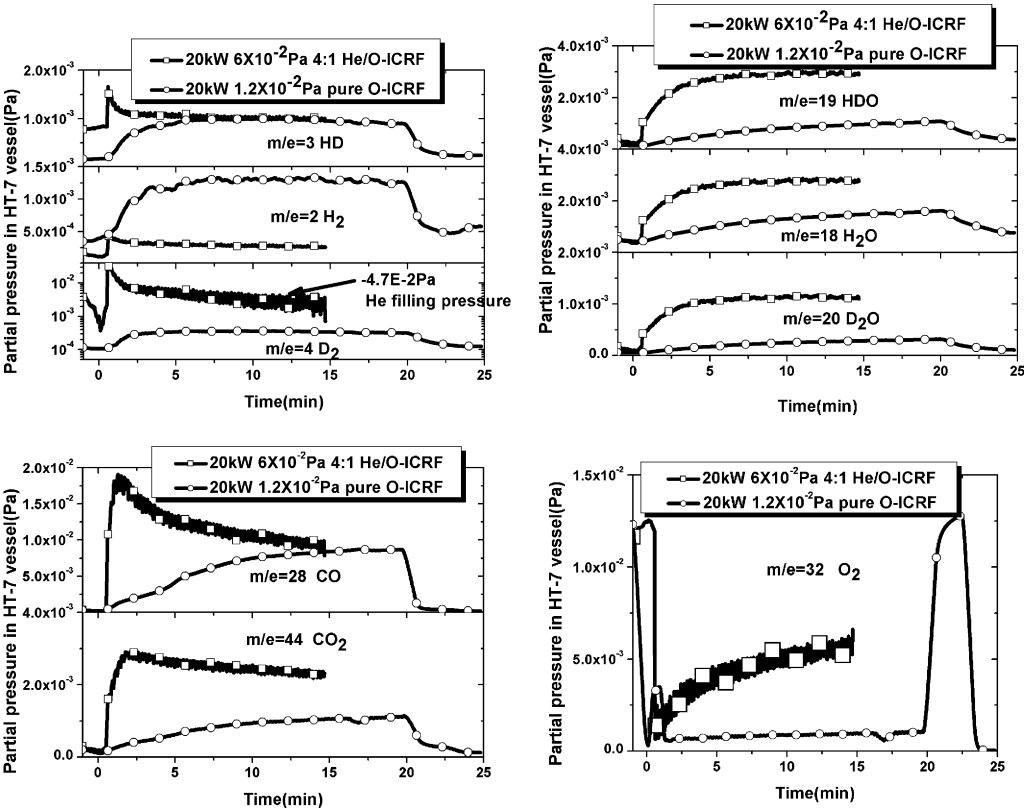

Fig. 3. Time evolutions of the P.P of molecules in 20 kW pure O-ICR and 4:1 He/O-ICR cleaning with an initial partial pressure of oxygen at 1.2×10^{-2} Pa.

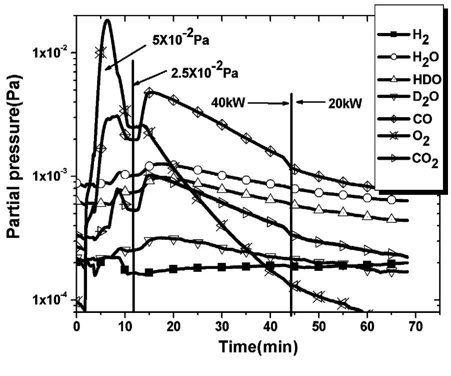

Fig. 4. Time evolutions of the P.P of particles in typical He-ICR cleaning after He/O-ICR experiment.

3.2. Influence of ICR power and cleaning pressure

The removal rates of H, D, C,O atoms could be calculated from the sum of their different forms, for example, the H atoms removal rate is the sum of the removal rates of $H_2 \times 2 + H_2O \times 2 + HDO$ as the following equation:

$$RR_{\text{H-atoms}} = 2 \times P_{H_2} \cdot S_{H_2} \cdot N_0/R \cdot T + 2 \times P_{H_2O} \cdot S_{H_2O} \cdot N_0/R \cdot T \times 2 + P_{HDO} \cdot S_{HDO} \cdot N_0/R \cdot T$$

As noticed in Ref. [19], on ‘clean’ walls, in the He-ICR cleanings, the removal rate of O-atoms was lower than that without ICR injection, indicating some oxygen retention happened on the walls. In D_2-ICR cleanings, only in the case of 0.1 Pa, independent on the power of 20 kW or 40 kW, the high removal rate of O-atoms indicates that the oxygen release was higher than retention. However, even if the He-ICR and D_2-ICR cleanings is not suitable for O removal on ‘clean’ walls, the calculated O and C removal rate in the detected gas increased with the increase of power and pressure.

The high power and high pressure could improve H release, which is beneficial for reduction of H retention on the walls, as shown in the Fig. 5(a) and (b). The removal rate of H in D_2-ICR cleanings is much higher than that in He-ICR cleanings by a factor of 4–8. No mater of utilization of pure O_2

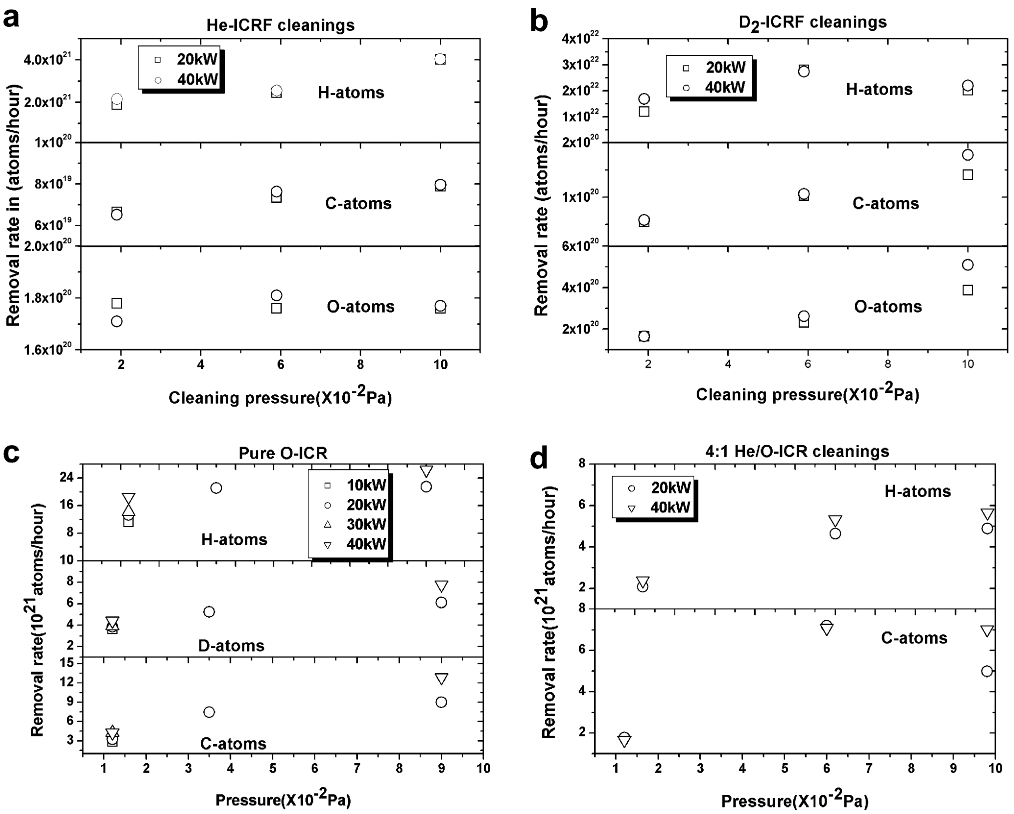

Fig. 5. Removal rates in different ICR cleanings with varies power and pressure. (a) He-ICR, (b) D_2-ICR, (c) Pure O-ICR, and (d) He/O-ICR).

or mix gas of He/O_2, the high power or high pressure O-ICR cleanings are beneficial for both deposit removal and hydrogen release, as shown in the Fig. 5(c) and (d).The removal rate of H and C in He/O-ICR is much lower than that in pure O-ICR cleanings, possibly due to different wall conditions [15,16].

The removal rate of C in both pure O-ICR and He/O-ICR cleaning is much higher than that in He or D_2-ICR cleanings by a factor of a few tens. During pure O-ICR cleanings, the removal rate of H is higher than that in He-ICR cleanings by a factor of 4–6, but is similar to that in D_2-ICR cleanings. The He/O-ICR cleanings has a small removal rate for H but still higher than that in He-ICR cleanings, possibly due to H removal during He-ICR and D_2-ICR cleanings, which was made two days before He/O-ICR cleanings.

As shown in Fig. 4, hydrogen release was very low during the He-ICR cleaning after He/O-ICR cleanings. Considering the H release in water (possibly absorbed during oxidation experiment), the H removal rate is about 5×10^{20} atoms/hour, which is much lower than that in He-ICR cleanings before oxidation experiment.

3.3. Total removed H and C

In Fig. 6, main procedures of cleanings and total removed H, C-atoms were shown. In the 120 min He-ICR experiment, a total number of 4.9×10^{21} H-atoms and 1.5×10^{20} C-atoms were removed. In the 120 min D_2-ICR experiment, a total number of 2.7×10^{22} H-atoms and 2×10^{20} C-atoms were removed. In the 270 min O-ICR experiment, a total number of 5.94×10^{22} H-atoms and 2.35×10^{22} C-atoms were removed. In the 160 min He/O-ICR experiment, a total number of 8×10^{21} H-atoms and 8×10^{21} C-atoms were removed.

3.4. Deposits removal

Deposits on samples were directly exposed to the 71 min 4:1 He/O-ICR and to the 240 min He-ICR + D_2-ICR plasma, respectively. Fig. 6 shows typical deposits with and without exposing to different

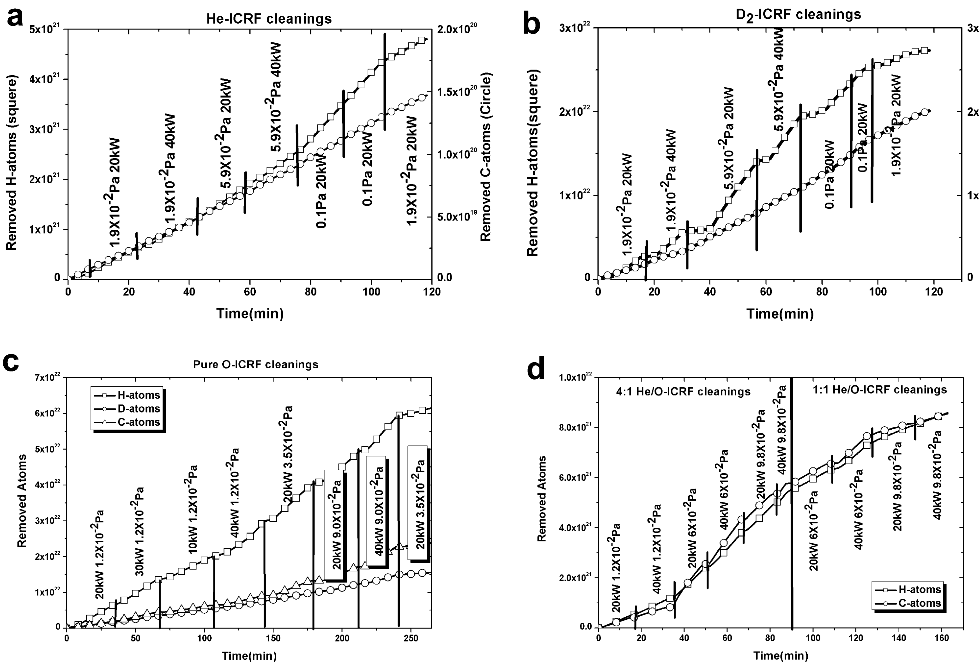

Fig. 6. Total removed H, C-atoms in different ICR cleanings (a) He-ICR, (b) D_2-ICR, (c) Pure O-ICR, and (d) He/O-ICR).

ICR plasmas on samples, which were cut from the same part of one limiter tile with apparent deposition after the HT-7 campaign in 2004. The Fig. 6(a) shows the deposited films without exposure to ICR plasmas. After exposing to the He/O-ICR plasmas, there are few deposits facing main plasma left on the samples, as shown in Fig. 6(b). However, after exposing to the He (D_2)-ICR plasma, the deposited film seems only to be broken without removal, as shown in Fig. 6(c). Those indicate that the He/O-ICR plasmas could effectively removal deposits whereas the He (D_2)-ICR plasma has little effect on deposits removal.

4. Discussions

ICR cleanings with various working gases, He, D_2, O_2, and gas mix of He/O_2, were investigated on hot walls with a temperature of 410–470 K. We can find that both the pure O-ICR and D_2-ICR cleanings had a higher removal rate for hydrogen than that in He-ICR cleanings by a factor of 4–6. The O-ICR cleaning had a much higher deposits removal rate than the He-ICR and D_2-ICR cleanings by a factor of a few tens. Exposing to the 71 min He/O-ICR plasmas, deposits could be effectively removed. However, exposed to the total 240 min He (D_2)-ICR plasma, the deposits were only partially removed. This also indicates high removal rate for deposits in O-ICR cleanings than that in He–ICR or D_2-ICR cleanings. Those results are beneficial for discussing and understanding the different mechanisms of hydrogen release in ICR cleanings with various working gases (see Fig. 7).

Before discussion of mechanisms of hydrogen release in ICR cleanings with various working gases, we should know the different mechanism of hydrogen retention. In a carbon limiter tokamak, H retention occurred by implantation and co-deposition. Carbon differs from metals in the behaviors of implanted hydrogen, mainly because of the C–H chemical reactivity. H retention by implantation would reach a saturation concentration, and up to 0.4–0.5 H/C at room temperature. Moreover, deposition of carbons occurs in plasma discharge due to physical and chemical sputtering. Fuel retention is associated with co-deposition of C layers [24]. In JET, due to this hydrocarbon migration, the build up of re-deposited layers near the inner divertor corner is related with the corresponding accumulation of fuel, which is dependent on duration of plasma operation [25].The deposited carbon becomes part of the hydrogen-saturated layer with H/C ~ 0.8–1, which increases in thickness with time. This leads to a hydrogen coverage, which increases linearly with exposure time. A key difference between

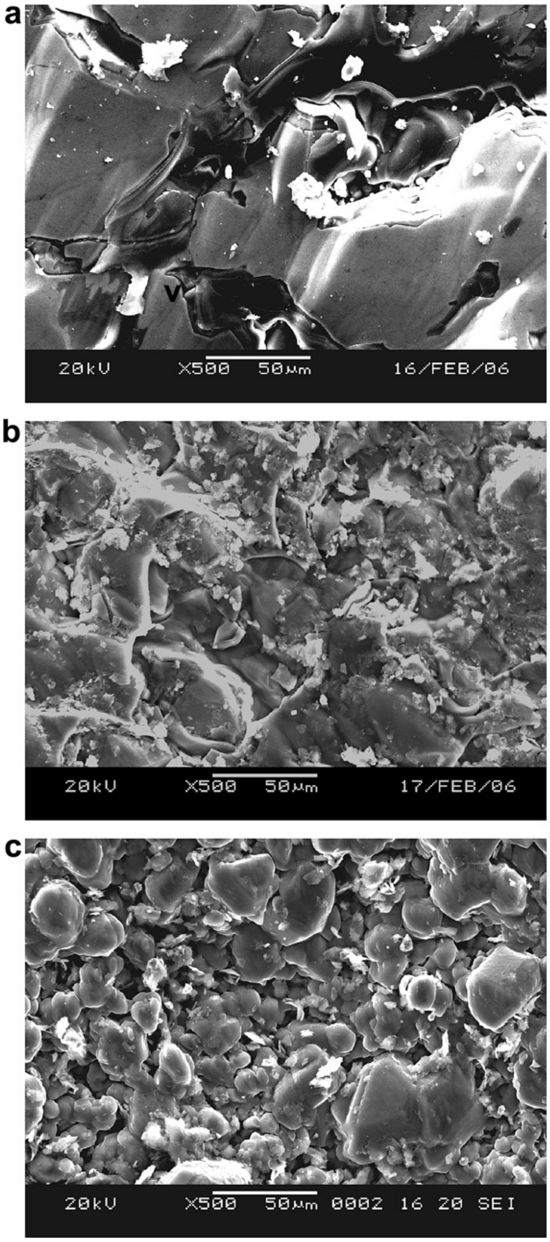

Fig. 7. Deposits on samples exposed to ICR plasmas. (a) Deposits without exposing, (b) deposits exposed to 120 min He-ICR and 120 min D_2-ICR plasma, and (c) deposits exposed to 71 min 4:1 He/O-ICR plasma).

hydrogen retention by implantation and co-deposition is the thickness of the hydrogen-containing layer, which is unlimited for co-deposition but is limited to the ion range (tens of nanometer, depending on the ion energy) for implantation [6].

During ICR cleanings, the working gas would be ionized, forming ions with different charges. With suitable parameters, the ion would obtain energy from ICR wave with resonance absorption. The energetic particles would impact the walls and lead release of gases from the walls. H removal in those discharges occurs via a combination of processes: chemical erosion, physical sputtering, ion induced desorption and isotopes exchange [6]. Especially, because oxygen is active with C and H, H release happens together with the deposit removal due to chemical erosion in oxidation wall conditioning [8–11]. Those physics base would be beneficial for understanding the differences among ICR cleanings with various working gases in HT-7.

During ICR cleanings, the wall temperature was about 400–470 K, which is much lower than 800 K required for thermal release of hydrogen [26,27]. Thus, thermal release of hydrogen during ICR cleanings could be ignored.

During He-ICR cleanings, ion-induced release of hydrogen is possible main procedure. If carbon implanted to saturation with hydrogen, hydrogen would be released when bombarded on carbons by non-hydrogenic ions such as helium ions, but this bombard is limited to the ion range and hydrogen release is also limited. However, in D_2-ICR cleanings, beside ion-induced release, hydrogen could be released due to isotope exchange. This is the main possible reason that D_2-ICR has more efficiency for H removal than He-ICR cleanings.

As a promising in-situ co-deposits removal technique, O-ICR has high removal rate for both H and C removal. During O-ICR cleanings, carbon layers were removed by formation of CO and CO_2 and that the incorporated hydrogen was primarily released in the form of water. In O-ICR cleanings, the energetic O particles (O^{2-}, O, O_2) would induce sputtering and at some time created oxygen atoms could access shaded areas. It is a possible reason that C removal rate is much higher than that in He-ICR or D_2-ICR cleanings. If He were added into O-ICR cleanings, the energetic He particles would possibly prevent the formed oxides, such as water and carbon-oxides, from absorption on the walls. Then, He in O-ICR plasma seems to promote the reaction of O–C, O–H and to reduce O retention on walls.

In other side, the wall, such deposit style (soft or hard film) and distribution, and hydrogen retention, would influence the efficiency of ICR cleanings. The efficiency for oxygen removal of He-ICR cleanings was much difference between on ‘clean’ walls and on walls with oxygen contamination [19]. H removal rate in He-GDC cleanings before and after the O-GDC experiment was much different [17]. In this paper, it is also shown that H removal rate in He-ICR cleanings after oxidation was much lower than before. Possibly, the D is reactivity with O may possibly be response for the higher O removal rate in D_2-ICR than in He-ICR cleanings. However, on the walls without oxygen pollutions, both He-ICR and D_2-ICR have little efficiency for both O and C removal.

The pure O-ICR experiment in 2004 and the He/O-ICR experiment in 2005 were performed after a campaign of HT-7 with 11000 and 6200 deuterium plasmas, respectively. The He-ICR and following D_2-ICR cleanings were done two days before the He/O-ICR experiment in 2005. Thus, it is possible that due to H removal during He-ICR and D_2-ICR cleanings, the removal of H and C was adjacent in the following He/O-ICR cleanings, whereas the removal of H was much higher than C in O-ICR cleanings in 2004. Other possible factors were the different procedures in plasma operation, such as boronization, cleaning times and plasma parameters during the whole campaigns.

Besides of those differences between various ICR cleanings, it was also found that high power and high pressure in ICR cleanings, no mater of He, D_2 or O_2, have high efficiency for H removal. In high power ICR cleanings, the ions energy should be high and could induced more H release in deep deposits. Especially, during O-ICR cleanings, energetic O particles would promote oxidation with C and H. In high pressure ICR cleanings, more particles would take part in the interaction with plasma facing materials and led more H release.

Investigation of ICR cleaning techniques for deposit removal and hydrogen release would be useful for wall conditioning in future device, such as EAST and ITER. To apply ICR cleaning technique should depend on deposits and hydrogen retention on walls, and also depends on requirement of plasma operation and safety. In most cases, different ICR cleaning techniques should be reasonably arranged.

Tritium retention in plasma facing materials has emerged as a primary concern for next step fusion devices fuelled with mixtures of D and T. The T retention should be low on the walls that could permit the device to continue plasma operation within the licensed inventory limit (about 350 g in ITER). An excessive T inventory in the torus would also present a safety hazard in the form of a potential T release to atmosphere, which would pollute environment and harm personal health (the limit is about 1 kg in ITER). The dominant mechanism for tritium retention in tokamak on carbon walls would be in co-deposition of eroded carbon with tritium [6,7]. Therefore, fast deposits removal and minimized T inventory on the walls are required in next step fusion devices.

The He-ICR and D_2-ICR cleanings without oxygen contamination on walls may be promising methods to reduce T inventory to lower than the limit for plasma operation. With T release due to isotopes exchange, D_2 (H_2)-ICR cleanings seems much better than the He-ICR cleanings. However, those methods only affect in a limited depth of co-deposits. If there are thick co-deposits with rich T, He-ICR and D_2-ICR cleanings is possibly not enough for T removal. Then O-ICR cleanings seems a better method for deposits removal and T release, especially, before venting of the torus for maintenance, in order to reduce the T outgassing and thus to minimize personnel exposure. Application of O-ICR cleanings (also O-GDC cleanings) may be the best way to remove co-deposits with rich T.

Even though the ICR cleanings could be done in presence of permanent magnetic field and suitable for future superconducting tokamaks, the efficiency of ICR cleanings should be improved. Both efficiency of ICR cleanings for deposit removal and H release should be promoted by high RF power and high conditioning pressure.

5. Conclusions

The differences between ICR cleanings with various working gases, He-ICR, D_2-ICR, O-ICR and He/O-ICR, were investigated after long deuterium plasma operation in the HT-7 machine on hot walls with a temperature of 402–470 K.

Different hydrogen release mechanism, such as chemical erosion, physical sputtering, ion induced desorption and isotopes exchange, could explain the difference of ICR cleanings with various gases. The wall conditions, such as deposits and hydrogen retention, would also influence the efficiency of cleanings for deposit removal and hydrogen release.

For each working gas, ICR cleanings with high power and/or high pressure could promote H release. Both the pure O-ICR and D_2-ICR cleanings had a higher removal rate of H than that in He-ICR cleaning by a factor of 4–6. The O-ICR had a much higher deposit removal rate than He-ICR and D_2-ICR cleanings by a factor of a few tens.

To apply ICR cleaning techniques in a superconducting tokamak device, such as EAST and ITER, should reasonable to be arranged, depends on deposits and hydrogen retention on walls, and requirement of plasma operation and safety.

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