Journal of Nuclear Materials 390–391 (2009) 929–933

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Comparison of O-ICR wall conditionings for limiter configuration in HT-7 and divertor one in EAST

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ARTICLE INFO

PACS:
52.40.Hf

ABSTRACT

Ion cyclotron resonance discharge-associated oxidation (He/O-ICR) wall conditioning was successfully carried out on full metallic material walls for a divertor configuration in EAST. Within a range of He/O-ICR parameters (5–20 kW, 1.2–7 × 10^{-2} Pa) in EAST, the highest removal rates (7.8 × 10^{22} H-atoms/h, 4.2 × 10^{22} C-atoms/h) were obtained with 20 kW and 7 × 10^{-2} Pa He/O-ICR. These rates are about 10 times higher than those in HT-7. Oxygen retention rates were lower than HT-7 by a factor of >10. Results of O-ICR cleanings in both EAST and HT-7 showed that power density, working pressure, plasma-facing area and materials, and pumping speed are the main factors influencing the co-deposit removal rates during O-ICR wall conditioning.

1. Introduction

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. 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 [1,2]. Oxidation wall conditioning on hot walls is a promising technique for in-situ co-deposit removal and it has been carried out in TFTR [3], TEXTOR [4–6], AUG [6,7], HT-7 [8–10]. Oxidation studies have also been performed in laboratories on deposits removal from TFTR, AUG, JET, DIII-D [11–15]. Ion cyclotron resonance discharge–associated oxidation (O-ICR) in HT-7 showed that it is a promising method for T removal in ITER in the presence of a permanent magnetic field. The O-ICR in HT-7 has a deposit removal rate of a factor of ~20 higher than that of He-ICR. To remove the retained oxygen from walls, He-ICR was also found to be effective. Plasma discharges could be recovered after the oxidation experiments [8–10].

EAST is a non-circular advanced steady-state experimental superconducting tokamak [16]. In the initial phase of EAST with full metallic walls, the ICR technique was investigated for cleaning, boronization and oxidation. In 2007, He/O-ICR cleanings of hot walls (~150 °C) were successfully carried out with various power and pressure. The main motivations included: (1) comparison with the results obtained on the carbon limiter tokamak–HT-7; (2) assessment of the application of He/O-ICR wall conditioning in a divetor tokamak; and (3) providing database for comparison with the He/O-ICR cleaning to be performed in the near future in EAST with carbon walls. This results will be useful for the application of He/O-ICR wall conditioning in the future devices, such as ITER.

2. Experiment setup and procedures

The EAST device (R = 1.75 m, a = 0.4 m) is the first tokamak in the world with a full superconducting advanced divertor configuration [16]. Its purpose is to establish a scientific and technological basis for the next generation of tokamak reactors. The superconducting coils can create and maintain a steady-state toroidal magnetic field of up to 3.5 T. For divertor operation, an elongation of 1.2–2 with single and double-null divertor configurations will be used. In the initial phase of EAST in 2006 and 2007, the first walls were fully made of stainless steel with a Mo limiter. The total plasma-facing areas was about 50–60 m^2. Hydrogen plasmas were achieved with circular and non-circular configurations and a high fraction of H_2 (up to 60–70%) was found in the residual gases.

He/O-ICR cleanings (the ratio of He to O_2 was 1:1) with wave frequency of 30 MHz have been performed in the presence of a permanent toroidal magnetic field of 1 T in EAST. Two dedicated ICRF antenna located at low field side were used for ICR wall conditioning. The RF power was in a range 3–20 kW and the working pressure was varied from 1.4 × 10^{-2} Pa to 7 × 10^{-2} Pa. The duty cycle of the ICR wave was set at 0.3 s on /1.2 s off. During He/O-ICR cleanings, the wall temperature was ~150 °C. Four turbo-pump stations with nominal pump speed of 12 m^3/s were used for particle exhaust. The influence of RF power, working pressure and magnetic field on the He/O-ICR cleaning efficiency was investigated. He-ICR cleanings performed before and after oxidation experiment

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doi:10.1016/j.jnucmat.2009.01.238

Table 1
Parameters of oxidation experiments on EAST.

	1	2	3	4	5	6	7	8	9
ICR cleaning	He	He	He/O	He/O	He/O	He/O	He/O	He/O	He
Pressure (10^{-2} Pa)	1.4	1.4	1.4	1.4	1.4	5	7	1.4	5
Power (kW)	20	20	5	10	20	10	10	5	20
Duration (min)	8	11	9	16	12	10	10	12	55

was also used for studying for oxygen removal. The experimental procedure is listed in Table 1.

3. Results

3.1. Partial pressures of reaction products during O-ICR discharges in EAST

Fig. 1 shows the behavior of partial pressures (P.P) of neutral gases during He-ICR, oxygen injection and He/O-ICR cleaning in EAST. During the 1st and 2nd He-ICR (at ~15 min and ~30 min, respectively), the P.P of H_2 increased whereas the P.P of impurities decreased, which indicates that He-ICR was beneficial for H_2 removal but not useful for removing impurities at the present wall condition.

After O_2 injection just after the 2nd He-ICR at 45 min., the P.P of CO, CO_2 and H_2O increased quickly by a factor of ~1000, whereas that of H_2 decreased, which was typical for thermo-oxidation. However, the P.P of oxides decreased, special that of CO which decreased very fast, implying that H and C removal during thermo-oxidation was sustained only for a short duration. Injection of the 3rd ICR wave at ~50 min resulted in abundant oxides production, which was beneficial for C and H removal.

With the same cleaning parameters (20 kW, 1.4×10^{-2} Pa), the P.P of CO and CO_2 during the He/O-ICR at ~90 min were much higher than during the 2nd He-ICR, indicating the presence of oxygen in the He/O-ICR was beneficial for carbon removal. At the same time, the P.P of H_2 was much lower than in the He-ICR whereas that of H_2O was considerably higher than in the He-ICR, which indicated that H_2 transferred to H_2O due to oxidation reaction during He/O-ICR wall conditioning.

As shown in Fig. 2(a), it was found that with the same ICR power(20 kW), the higher the working pressure, the higher was the P.P of H_2 and oxides, such as CO, $CO_2$and H_2O. Fig. 2(b) also showed that with the same He/O_2 working pressure (1.4×10^{-2} Pa), the higher the ICR power, the higher was the P.P of H_2 and oxides. These results indicate that high power and/or high pressure in He/O-ICR promote C–O and H–O reactions, which are and beneficial for C and H removal.

Wall condition is also expected to influence on the removal efficiency of deposits by He/O-ICR. With the same cleaning parameters (5 kW, 1.4×10^{-2} Pa), the P.P of H_2 and CO in the last He/O-ICR was

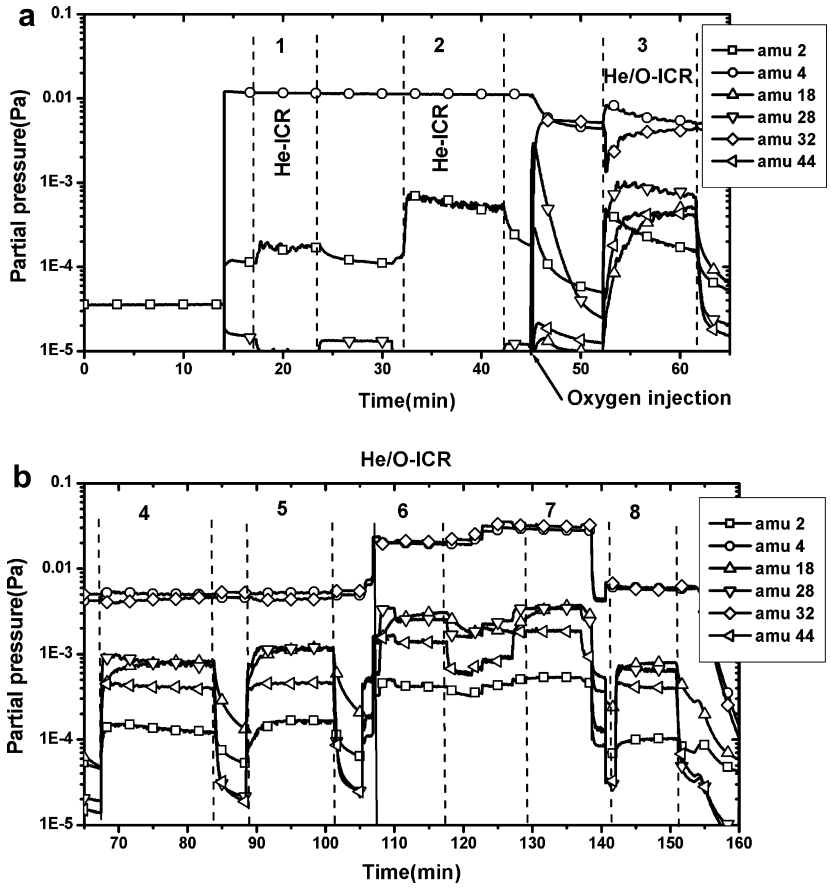

Fig. 1. Behavior of the partial pressures of neutral gases during He-ICR cleaning, oxygen injection, He/O-ICR wall conditioning in EAST.

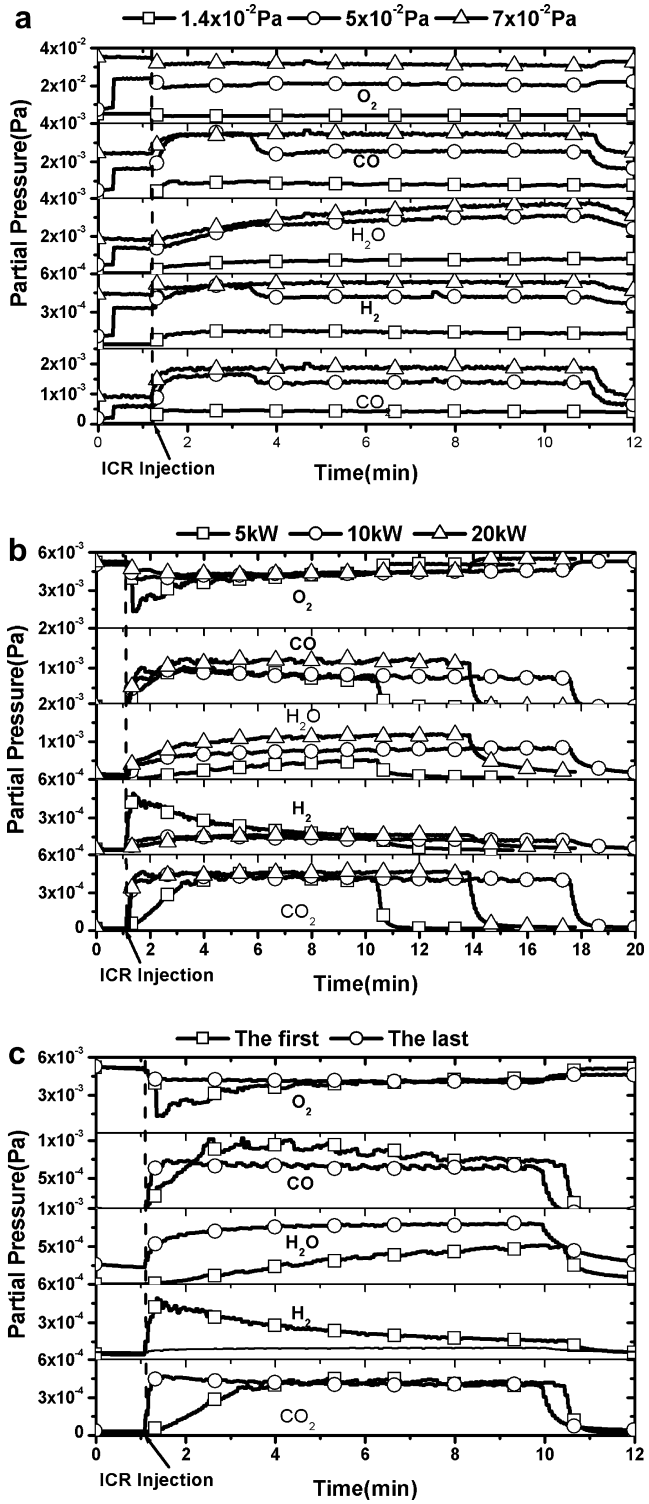

Fig. 2. Influence of (a) pressure, (b) power and (c) wall condition on the partial pressures of neutral gases during He/O-ICR cleanings in EAST. (a) Pressure influence (at 20 kW ICR power); (b) power influence (at 1.4×10^{-2} Pa He/O_2 pressure); and (c) wall condition influence (at 5 kW ICR power and 1.4×10^{-2} Pa He/O_2 pressure).

lower than that in the first one, whereas the P.P of H_2O was higher in the last He/O-ICR, as shown in Fig. 2(c). The possible reason for this observation is that during the long He/O-ICR, the amount of H and C on the walls was reduced and lead water production.

After He/O-ICR cleanings, normal He-ICR was used for wall recovery. As shown in Fig. 3, during the He-ICR cleaning at

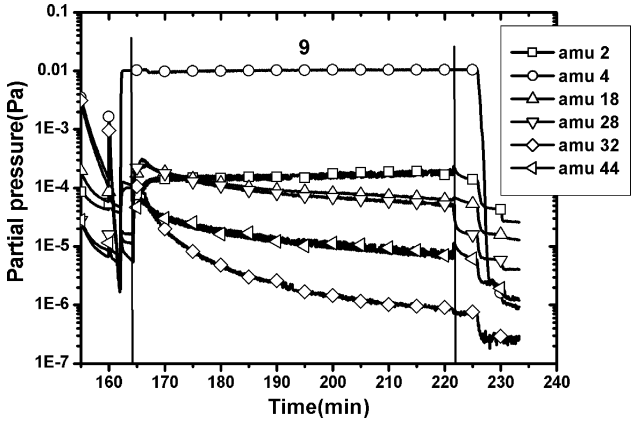

Fig. 3. Oxygen removal by He-ICR cleaning after He/O-ICR experiment in EAST.

~160 min after He/O-ICR, the P.P of impurity gases, such as CO, CO_2 and H_2O, increased at the start of the ICR injection, indicating this cleaning was useful for oxygen removal. As the He/O-ICR continued, the P.P of impurities gradually decreased during this cleaning indicated the oxygen content in the vessel has also decreased.

3.2. H and C removal rates in EAST

During the experiment with discharge time of 70 min, total 5.2×10^{22} H-atoms and 3×10^{22} C-atoms were removed from the vessel. Based on the experimental parameters for the 20 kW 7×10^{-2} Pa He/O-ICR, the highest removal rates for H and C are estimated to be 7.8×10^{22} H-atoms/h and 4.2×10^{22} C-atoms/h, respectively,. The higher the pressure and/or power, the higher were the removal rates of oxides, H and C, as shown in Fig. 4.

With the same parameters (20 kW, 1.4×10^{-2} Pa), the He/O-ICR had a factor of two higher removal rate for hydrogen than the 2nd He-ICR, and the He/O-ICR had a factor of 250 higher removal rate for C than the He-ICR. Due to effective removal of H and C during the long He/O-ICR operation, the H and C removal rates during the last He/O-ICR(8th) were lower than those seen in the first one(3rd).

On the metal walls of EAST, compared to thermo-oxidation at low pressure without ICR (only oxygen filling), ICR injection promoted the oxidation of H and C, and the P.P of released reaction products were influenced by ICR power, working pressure and wall conditions. High power and/or high pressure in He/O-ICR cleanings were beneficial for H and C removal, similar to the results of O-ICR experiments in the HT-7 [8–10].

3.3. Oxygen removal and retention

During He/O-ICR cleanings, a total of 1.9×10^{21} O-atoms were retained on the walls. If averaged over a plasma-facing surface area of 50–60 m^2, an oxygen coverage is estimated to be $3.2–3.8 \times 10^{19}$ O-atoms/m^2 on the walls. During the subsequence He-ICR cleaning, about 6×10^{20} O-atoms were removed from the vessel, leaving an oxygen coverage of $2.2–2.6 \times 10^{19}$ O-atoms/m^2 on the walls.

3.4. Comparison of He/O-ICR between HT-7 and EAST [8–10]

In both HT-7 and EAST, during He/O-ICR cleanings, C was removed by the formation of CO and CO_2 and most of the hydrogen was released in the form of water molecules. He/O-ICR was more effective than He-ICR for deposit removal and hydrogen release. H and C removal rates increased with increasing working pressure or power. Low pressure and/or high power were beneficial for reduction of O retention on the walls. Both H and C removal rates

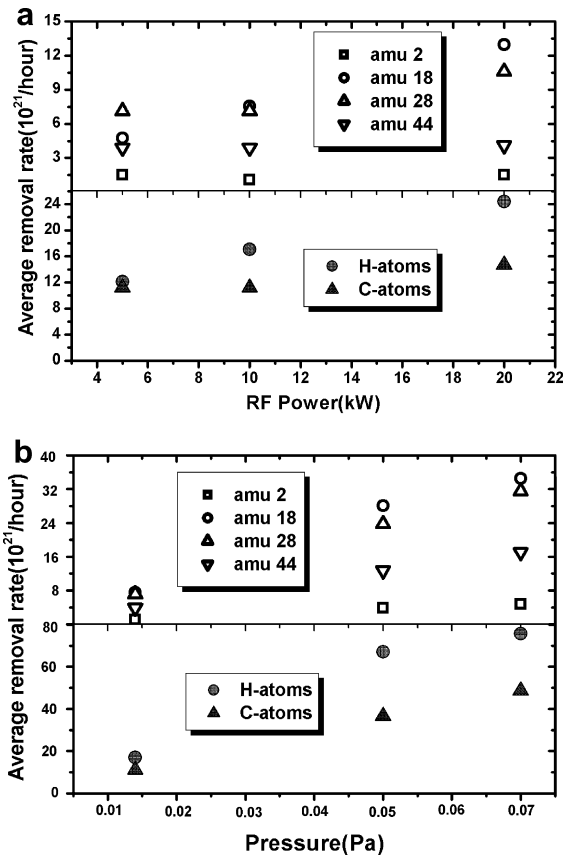

Fig. 4. Influence of (a) ICR power, and (b) He/O_2 pressure on particleremoval rates during He/O-ICR cleanings in EAST. (a) ICR power influence, and (b) He/O_2 pressure influence.

in EAST were higher than in HT-7 by a factor of ~10. With the same parameters (20 kW 1.4×10^{-2} Pa) H and C removal rates during He/O-ICR cleaning in HT-7 were 2×10^{21} H-atoms/h and 1.9×10^{21} C-atoms/h, whereas they were 2.5×10^{22} H-atoms/h and 1.3×10^{22} C-atoms/h in EAST. The average O retention rates (3×10^{18} O-atoms/$m^2 \cdot h$) during He/O-ICR cleanings in EAST were much lower than those in HT-7($1.8–4.8 \times 10^{19}$ O-atoms/$m^2 \cdot h$).

The factors influencing C and H the removal efficiency of He/O-ICR cleanings include the first wall structure and materials, plasma fuels, plasma volume, plasma-facing surfaces, pumping speed and RF antenna. The parameters used for O-ICR in HT-7 and EAST are listed in Table 2. The ICRF plasma volume of EAST is ~12 m^3 whereas that of HT-7 is ~2.6 m^3, which would influence the energy density during He-ICR cleaning. The plasma-facing surfaces in EAST are about 50–60 m^2 whereas the area in HT-7 are ~12 m^2, which would influence the effective cleaning areas. The plasma-facing material in the present study in EAST was fully metallic (stainless steel wall and Mo limiters) whereas HT-7 has 20% doped graphite with SiC coating, which would influence the cleaning ability on the surfaces. EAST is a divertor machine whereas HT-7 is a limiter device, which would influence the cleanings zone. The plasma fuel in EAST was H_2, whereas it is D_2 in HT-7.

In HT-7, the carbon walls, comprising ~20% of PFC surface, would supply a large source of C for co-deposit formation whereas in EAST, without C walls, carbon–boron films formed during boronization (ICR + $C_2B_{10}H_{12}$) would provide C sources for co-deposit formation. In EAST, besides releases from stainless steel and boron films, H retention on metal walls during plasma discharges should be the main source of H during He/O-ICR cleaning. However, in HT-7, due to only D_2 plasma operation, most H would come from the stainless steel materials (80% H_2 from the walls), boron films and co-deposits. These differences in H source may explain why more O_2 reacted with H and fewer O_2 reacted with C during He/O-ICR cleaning in EAST than in HT-7. Oxygen retention on stainless steel walls was much lower than that observed in carbon walls. O would easily diffuse in carbon materials and form strong C–O absorption bonds. However, on stainless steel walls, high energy O particles would form a thin metal-oxide film, which possibly could limit further oxidation on metal walls.

Assuming that H and C removal rates linealy on plasma volume and plasma-facing surface area, then the removal rates of H and C in EAST could be expressed as:

$$RR_{EAST}/RR_{HT\text{-}7} = V_{HT\text{-}7} \times S_{EAST} \times PS_{EAST}/(V_{EAST} \times S_{HT\text{-}7} \times PS_{HT\text{-}7}) = 12.8$$

RR is the removal rate, *V* is the plasma volume, *S* is the area of plasma-facing surface, and *PS* is the pumping speed. It was found that the plasma volume, plasma-facing surface area and pumping were the main factors influencing H and C removal rate during He/O-ICR cleaning. The others factors, such as wall structure and RF antenna, only contribute about 1.1 and 0.6 times, respectively, for H and C removal rates during He/O-ICR in EAST than that in HT-7.

With a similar assumption of H and C removal rates linealy on plasma volume and plasma-facing surface area, the removal rate of C in ITER could be predicted using the various parameters from the HT-7 or EAST results, see in Fig. 5. To remove 700 g T in ITER (1–2 g C deposited on the walls in a 1000 s plasma discharge and

Table 2
Parameters for He/O-ICR cleaning in HT-7 and EAST.

	EAST	HT-7
Configuration	Divertor	Limiter
Material of PFCs	Stainless steel walls (>99%) Mo limiter (<1%)	Doped graphite limiter (20%) Stainless steel liners (80%)
Plasma	H_2	D_2
Plasma-facing areas	~50–60 m^2	~12 m^2
Vessel volume	~40 m^3	~5 m^3
Plasma volume	~12 m^3	~2.62 m^3
Pumping speed	~10^4 l/s	~850 l/s
RF antenna	Specially designed for wall conditioning Low field side	For both wall conditioning and heating High field side

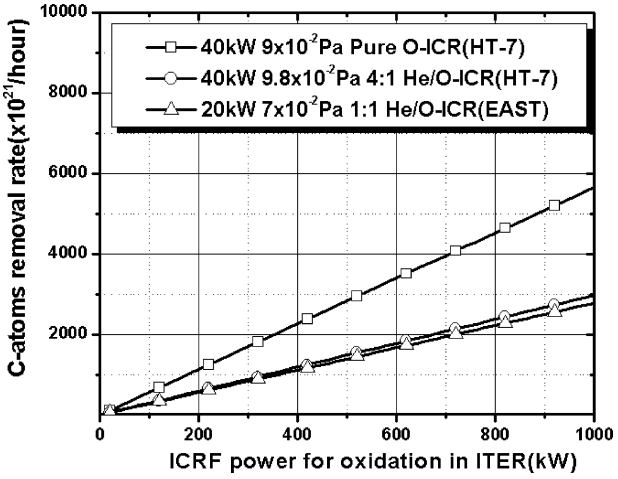

Fig. 5. Predicted particle removal rates in ITER based on O-ICR from HT-7 and EAST results.

assuming $T/C \sim 1$ in the co-deposits), it would require 12–22 h of wall conditioning with 1 MW O-ICR discharges.

4. Conclusions

He/O-ICR wall conditionings was successfully carried out on full metallic material walls for a divertor configuration in the ITER-relevant full superconducting EAST tokamak in 2007. Within the experimental parameter range in EAST (5–20 kW, $1.2–7 \times 10^{-2}$ Pa) in EAST, the highest removal rates (7.8×10^{22} H-atoms/h and 4.2×10^{22} C-atoms/h) were obtained with 20 kW and 7×10^{-2} Pa He/O-ICR. These rates are about 10 times higher than that in HT-7. However, the O retention rates were lower than those in HT-7 by a factor of >10. Results of O-ICR cleanings in both EAST and HT-7 showed that power density, working pressure, plasma-facing area and materials and pumping speed are the main factors influencing co-deposit removal during O-ICR wall conditioning. The dependence of removal rates on these factors could be used to estimate the *T* removal rate in the future devices, such as ITER.

A similar experiment will be carried out in EAST with carbon walls (50–60 m^2) in the near future, enabling us to compare He/O-ICR wall conditioning with different plasma-facing materials.

Acknowledgements

This work was funded by the National Nature Science Foundation of China under Contract No. 10705030. This work was also partly supported by the JSPS-CAS Core-University Program on Plasma and Nuclear Fusion.

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