



ICRF wall conditioning and plasma performance on EAST

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ABSTRACT

ICRF (ion cyclotron resonance frequency) wall conditioning was performed on EAST superconducting tokamak. It included ICRF cleaning in-between shots, boronization associated with ICRF plasmas, and ICRF oxidation with an ITER-relevant full metallic wall material. A dedicated ICRF antenna was developed for wall conditioning on EAST. The RF frequency is 30 MHz, and maximum output power of RF system is 300 kW. The duty time of pulsed ICRF wave was set at 0.3 s on and 1.2 s off in presence of the toroidal magnetic field of 1–2 T. Optimization of start-up, ramp-up and plasma shaping for single and double-null configurations were obtained following the ICRF wall conditioning. High density, high plasma current and long pulse discharges were achieved on EAST.

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1. Introduction

First plasma was obtained in the experimental advanced superconducting tokamak (EAST) on September 26th, 2006 [1–5]. Single-null and double-null diverted plasmas were achieved successfully in the EAST tokamak on January 22nd, 2007 [6,7]. EAST is a first full superconducting tokamak with most advanced configuration in the world [2,3]. The former name of the EAST tokamak was HT-7U [2]. The use of full superconducting poloidal field coils on EAST is the first trial test in the world for the sake of international thermonuclear experimental reactor (ITER). To achieve the steady state operation the EAST comprises 16 D-shaped superconducting toroidal field coils, which can create and maintain a toroidal magnetic field B_T up to 3.5 T. The key components of EAST are 14 superconducting poloidal field coils, current leads and superconducting buslines, vacuum vessel, thermal shields, cryostat, divertor and in-vessel components. Fig. 1 shows a photo of the EAST vacuum vessel, where the first wall was stainless steel with a Mo limiter. The scientific mission of the EAST project is to study the physical issues involved in steady state advanced tokamak devices, while its engineering mission is to establish and support the technology basis of fully superconducting future fusion reactors.

Wall conditioning techniques have been developed and applied in tokamaks for impurities and hydrogen removal [8,9], such as glow discharge cleaning (GDC) [10], as well as various other methods based on RF techniques at electron cyclotron resonance (ECR) [11] and ion cyclotron resonance (ICR) [12]. However, extrapola-

tion 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 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. 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, ICRF 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 [12] and Textor with He [13].

ICRF cleaning with helium (He-ICRF), ICRF boronization, and ICRF oxidation (O-ICRF) were studied recently on EAST tokamak [14,15] with an ITER-relevant full metallic wall material. Improvements of plasma performance were achieved following the ICRF wall conditioning.

2. Experimental setup

The EAST device parameters included a major radius of $R = 1.75$ m, minor radius of $a = 0.4$ m, aspect ratio of 4.25, an elongation rate of 1.2–2, and multi-configurations of single-null divertor, double-null divertor and circular configurations with a limiter. The first wall was made of full stainless steel, and total plasma facing areas was about 50–60 m². The main operational parameters used for EAST experiments are: an ohmic heated hydrogen discharge with plasma current $I_p = 100$ –500 kA, a toroidal field of 2 T at $R = 1.75$ m, a line averaged density of 0.5 – 4×10^{19} m⁻³ and

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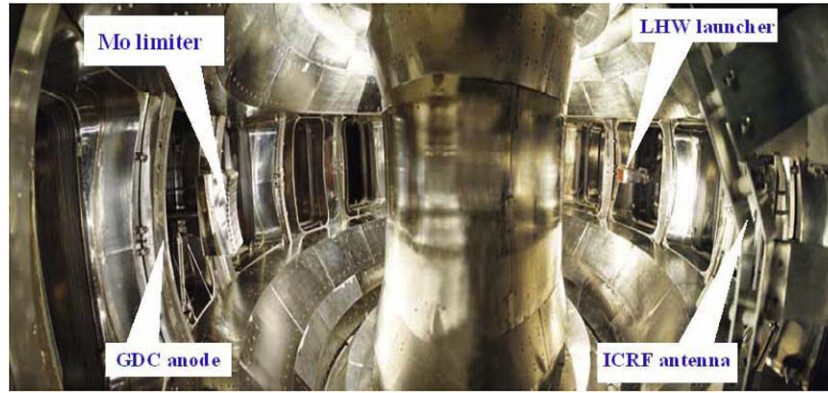


Fig. 1. A full metallic wall on EAST.

an edge value of safety factor of 2–10. The plasma diagnostics on EAST were as follows [6–18]: a vertical one-channel FIR hydrogen cyanide (HCN) laser interferometer at $R = 1.9$ m for measuring the line averaged density, a 10-channel soft X-ray array for intensity measurement, a 16-channel heterodyne ECE for measuring the profile of the electron temperature, a 8-channel XUV bolometer array to measure plasma radiation losses, a 3-channel hard X-ray array for intensity measurement, an electromagnetic measurement system of Rogowski coils, fluxloops and Mirnov coils, a 35-channel H_{α} radiation array, a 1-channel visible bremsstrahlung emission measurement, an impurity optical spectrum measurement system and two optical spectroscopic multi-channel analyzers (OMA). Two ICRF antennae were designed specially for wall conditioning on

EAST as shown in Figs. 1 and 2, which located at low field side. One of the two ICRF antennae is used. The RF frequency is 30 MHz, and maximum output power of ICRF system is 300 kW. One calibrated PKR251 Penning gauges were used to monitor the total pressure in the EAST vacuum vessel. A differential pumped system is composed of one turbo-pump station, one PKR251 gauge and a quadruple mass spectrometer (QMS). This QMS in the differential pumped chamber was used for measurement of the partial pressure of neutral gases during cleaning [17].

3. ICRF wall conditioning

ICRF cleanings were performed in presence of permanent toroidal magnetic field of 2 T at the interval of plasma discharges in EAST. The injected power (which means a RF power delivered to the antenna) for wall conditioning is from 3 to 20 kW, and the duty time of pulsed ICRF wave was set at 0.3 s on and 1.2 s off in this experiments. During He-ICRF cleanings, the wall temperature was about 80–130 °C. Four turbo-pump stations with nominal pump speed of 12 m³/s were used for particles exhaust. Fig. 3 shows a typical He-ICRF cleaning on EAST between H₂ plasma discharges. It is observed that H₂ partial pressure decreased fast due to exhaust by pumping and absorption on the walls after a H₂ plasma discharge. During He-ICRF cleaning in Fig. 3, H₂ would sustain at a high partial pressure, which was beneficial for its exhaust by



Fig. 2. The dedicated ICRF antenna for wall conditioning and a typical He-ICRF plasma, where the duty time of pulsed ICRF wave was set at 0.3 s on and 1.2 s off.

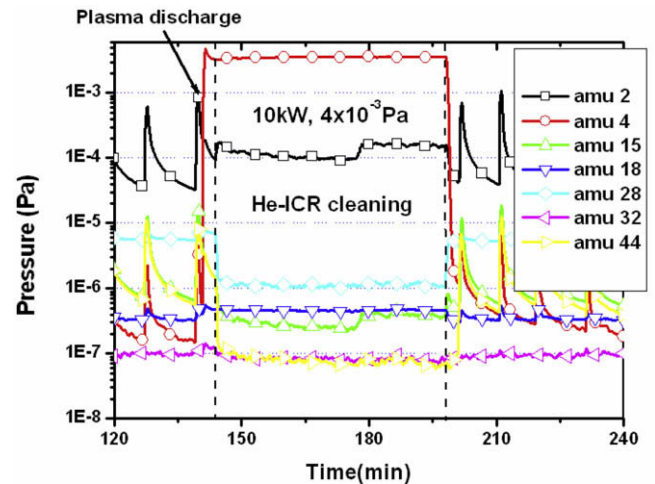


Fig. 3. Evolution of particles partial pressure during He-ICRF cleaning at the interval of H₂ plasma discharges, where the RF frequency is 30 MHz in presence of the toroidal magnetic field of 2 T.

pumping. After the He-ICRF cleaning, the H₂ plasma density was easily controlled, and plasma properties were improved. Influences of RF power and working pressure on the He-ICRF cleaning efficiency were investigated in Fig. 4. High RF power and high working pressure would promote H and C removal, as shown in Fig. 4(a) and (b), correspondingly. The highest H removal rate was 1.1×10^{22} H-atoms/h in 1.8×10^{-2} Pa and 20 kW He-ICRF cleaning, and the highest C removal rate was 1.3×10^{20} C-atoms/h in 1.8×10^{-2} Pa and 20 kW He-ICRF cleaning. Where the removal rate of C and H is defined in Ref. [18]. The working pressure was in a wide range from 4×10^{-3} Pa to 10 Pa. However, pumping speed decrease while the working pressure is over 0.3 Pa [14]. The pumping speed is very important for He-ICRF cleaning on EAST.

Boronization has been carried out on EAST for five times, among which two times was GDC boronization [1] and others were ICRF boronization [16]. The experimental setup is shown in Fig. 5. ICRF boronization system includes one small metal box for loading carborane (C₂B₁₀H₁₂) material, and one transfer pipe for introduction of carborane vapour into the plasma vacuum vessel (PVV). About 1 h of helium ICRF cleaning is applied in advance, which is helpful for the boron film coating. The ICRF power is 8 kW, and the period is 0.3 s on and 1.2 s off. The toroidal magnetic field is 1.2 T for ICRF boronization. All the four turbo-molecular pumps are used, and helium is puffed by the gas injection system keeping the PVV pressure at 9.3×10^{-3} Pa. To avoid the condensation of carborane vapour from blocking the gas line, the transfer pipe and the valves are heated up to 200 °C. For the benefit of enhancing impurity removal, the plasma facing component (PFC) boards are baked up to

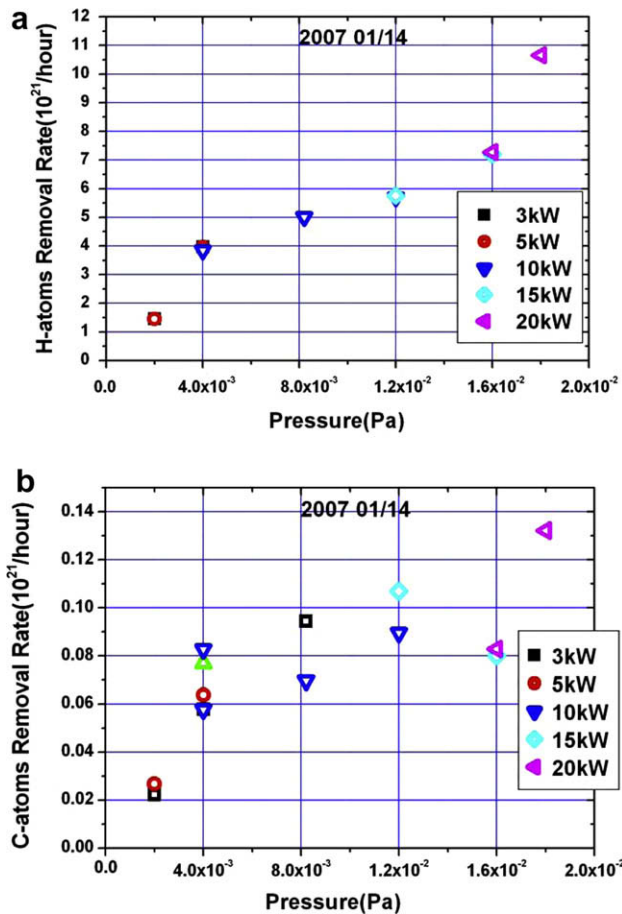


Fig. 4. (a) Average removal rates of H for different pressure and power in He-ICRF cleanings dated on Jan.14, 2007. (b) Average removal rates of C for different gas pressure and ICRF power.

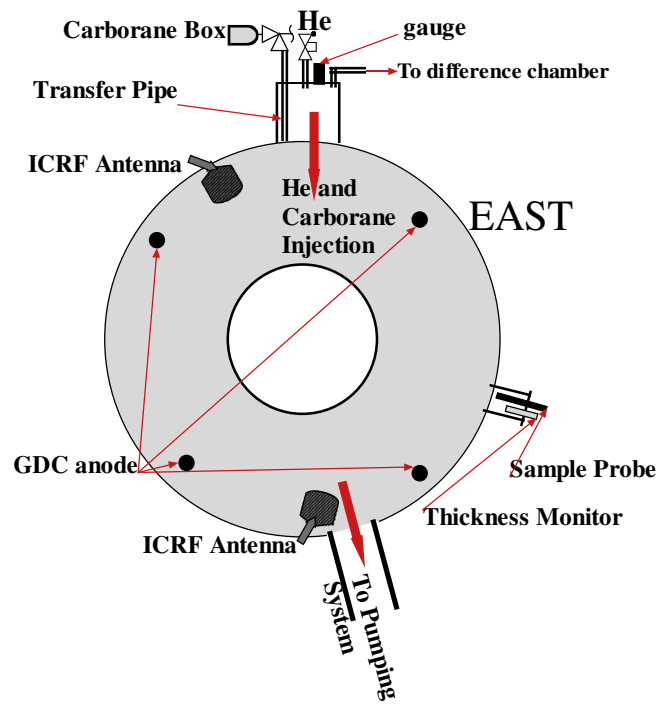


Fig. 5. Experimental setup for ICRF boronization on EAST.

120 °C. Fig. 6 shows a time evolution of the carborane box temperature, and partial pressure of boron material, released hydrogen and filling helium during ICRF boronization. During boronization, the power of ICRF wave is raised to 15 kW for 2 h to enhance the decomposition of the carborane molecules. The valve between the carborane box and the plasma vacuum vessel is opened, and the box is heated gradually. About 10 g of carborane is loaded for each time of boronization. To limit the consumption of carborane, pumping speed is decreased by shutting off 3 of 4 gate valves of the pumping system and only one TMP (turbo-molecular pump) is pumping. In this phase, the carborane temperature is a key issue because it greatly affects the throughput of the carborane vapour flow. In about 10 min the box is baked up to about 100 °C and then kept stable as shown in Fig. 6. The thickness of coated boron film is 200 nm, and the lifetime is about 1–2 weeks. Based on our experience [8,16–18], high H inventory level is always observed due to

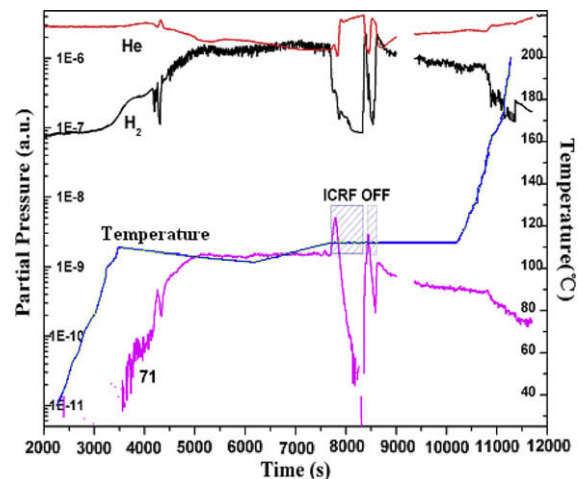


Fig. 6. Evolution of the carborane (C₂B₁₀H₁₂) box temperature, and partial pressure of boron material, released hydrogen and filling helium during ICRF boronization.

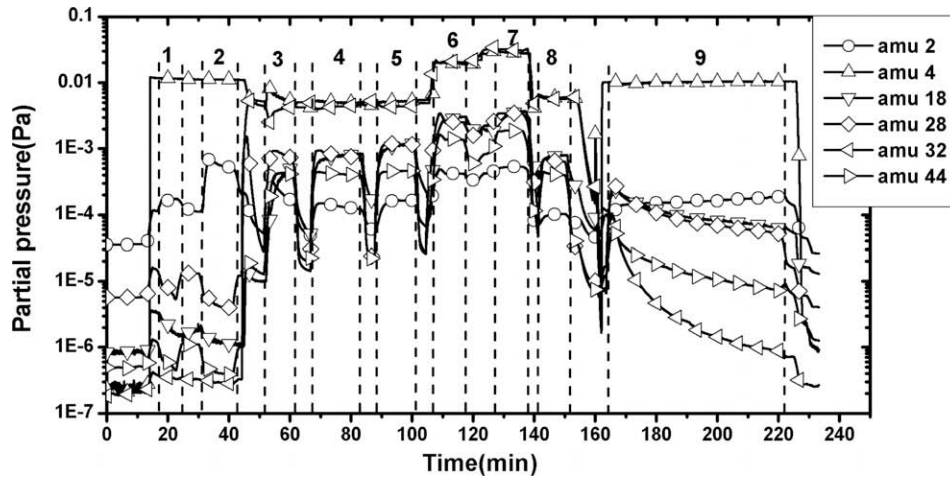


Fig. 7. Partial pressure during ICRF oxidations on EAST, where He-ICRF and O-ICRF parameters for each pulse are listed in Table 1.

Table 1
Parameters of gas pressure, ICRF power and gases during pulsed ICRF oxidation (see Fig. 7).

Pulse row	1	2	3	4	5	6	7	8	9
Pressure (10^{-2} Pa)	1.4	1.4	1.4	1.4	1.4	5	7	1.4	1.4
Power (kW)	20	20	5	10	20	20, 10	10	5	20
Gas	He	He	He, O	He, O	He, O	He, O	He, O	He, O	He, O

the large amount of H from the carborane ($C_2B_{10}H_{12}$). Therefore, after boronization the first and the most important task is to remove H from the vessel. Helium ICRF cleaning is very helpful. To limit the damage to the freshly deposited boron film on the first walls, the RF power is decreased to 5 kW for 1 h finally. For enhancement of out-gassing, the PFCs are kept at high temperature and all four TMPs are put into use.

ICRF oxidation was successfully carried out on EAST. The toroidal magnetic field was 1 T, and the ratio of working gases He to O_2 was 1:1. The duty time of pulsed ICRF wave was set at 0.3 s on and 1.2 s off. Fig. 7 shows the behaviors of particles partial pressure during He-ICRF and He/O-ICRF cleanings in EAST. Table 1 shows parameters of each power and pressure, and working gas for nine times conditionings correspondingly. The analysis result and discussion has been summarized in PSI-18 conference (P1-45#) as a

poster [15]. With He/O-ICRF parameters of 5–20 kW and $1.2\text{--}7 \times 10^{-2}$ Pa in EAST, the highest removal rate of 7.8×10^{22} H-atoms/h and 4.2×10^{22} C-atoms/h were obtained in the 20 kW and 7×10^{-2} Pa He/O-ICRF cleaning.

4. Plasma performance

Optimization of start-up, ramp-up and plasma shaping for single and double-null configurations were obtained following the ICRF wall conditioning. A discharge at plasma current I_p of 200 kA and toroidal field B_t of 2 T with a typical double-null configuration [7] was shown in Fig. 8. High density (line average density $\langle n_e \rangle$ is up to $4.1 \times 10^{19} \text{ m}^{-3}$, and where chord length L is about 1 m), high plasma current ($I_p = 0.5 \text{ MA}$ at $B_t = 2 \text{ T}$), and long pulse ($t_d \sim 10 \text{ s}$, $I_p = 0.2 \text{ MA}$ at $B_t = 2 \text{ T}$) discharges [6] were achieved fol-

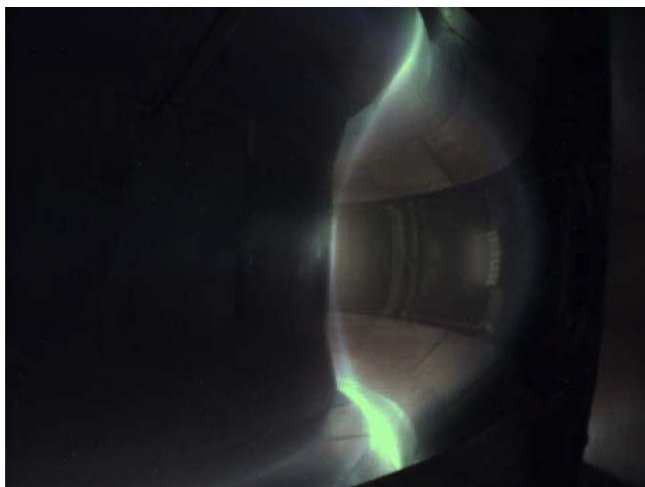


Fig. 8. A photo of double-null plasma on EAST (shot number 3745#), where plasma current $I_p = 0.2 \text{ MA}$, $B_t = 2 \text{ T}$, elongation of $\kappa = 1.8$, $\delta = 0.5$ at $t = 3.1 \text{ s}$.

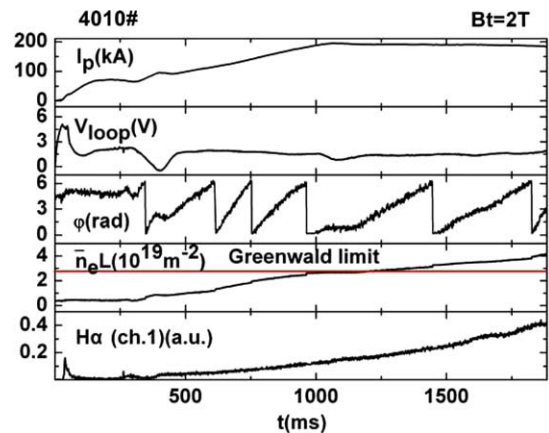


Fig. 9. High density (4010#) discharge was achieved on EAST, where Greenwald factor $f_{GW} = 1.4$, ϕ is phase shift of the HCN laser interferometer, and $\langle n_e \rangle L = 4.1 \times 10^{19} \text{ m}^{-2}$, plasma current $I_p = 0.5 \text{ MA}$ and $B_t = 2 \text{ T}$.

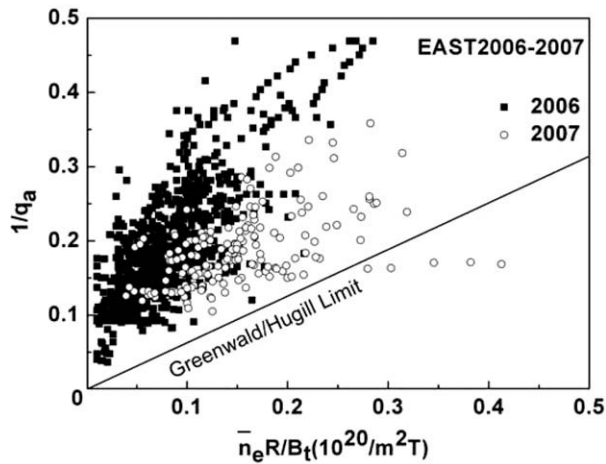


Fig. 10. Extension of operational region by feedback gas puffing and ICRF wall conditioning.

lowing the ICRF boronization on EAST. Fig. 9 shows a typical shot of high-density plasma, where Greenwald factor f_{GW} reached to 1.4. Fig. 10 shows a compare of Hugill plots in 2006 and in 2007. Plasma density was still low at lower q_a region in 2006, where pre-program gas puff and GDC boronization was used. Higher density at high plasma current and more stable operation are achieved by means of feedback pulse gas puffing and the ICRF boronization. Extension of the operational region and improvement of plasma performance are obtained in 2007.

5. Conclusion

ICRF cleaning with helium discharge (He-ICRF), ICRF boronization, and ICRF oxidation (O-ICRF) were performed on EAST with an ITER-relevant full metallic wall material. The dedicated ICRF antenna was developed for wall conditioning on EAST. The RF frequency is 30 MHz, and maximum output power is 300 kW in presence of the toroidal magnetic field up to 2 T.

The highest H removal rate was 1.1×10^{22} H-atoms/h in 1.8×10^{-2} Pa and 20 kW He-ICRF cleaning, and the highest C removal rate was 1.3×10^{20} C-atoms/h in 1.8×10^{-2} Pa and 20 kW He-ICRF cleaning. High RF power and high working pressure can enhance H and C removal. Time evolution of the carborane ($C_2B_{10}H_{12}$) box temperature, and partial pressure of boron mate-

rial, released hydrogen and filling helium during ICRF boronization were studied in detail. The thickness of coated boron film is 200 nm, and the lifetime is about 1–2 weeks. Analysis of samples shows that in the freshly deposited boron film there is large amount of B and the B–B bond is dominant, while after exposure to plasma the B–O is dominant [16]. ICRF oxidation was successfully carried out with different powers and different pressures on EAST. It is obtained that the highest removal rate are 7.8×10^{22} H-atoms/h and 4.2×10^{22} C-atoms/h in the 20 kW and 7×10^{-2} Pa by the He/O-ICRF cleaning.

Extension of the operational region and improvement of plasma performance are achieved following the ICRF wall conditioning. High density (average density $\langle n_e \rangle$ is up to $4.1 \times 10^{19} \text{ m}^{-3}$), high plasma current ($I_p = 0.5 \text{ MA}$ at $B_t = 2 \text{ T}$), and long pulse ($t_d \sim 10 \text{ s}$, $I_p = 0.2 \text{ MA}$ at $B_t = 2 \text{ T}$) discharges were achieved on EAST. Towards long pulse high power plasmas, actively water-cooling graphite wall and PFC will be available soon on EAST.

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