Boronization during the first plasma operation on EAST

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Abstract. Both ion cyclotron rf and glow discharge boronization have been successfully used for wall conditioning on EAST tokamak device. The whole process is monitored continuously by residual gas analyzer and film thickness monitor. These diagnostics provide detailed information about the boronization. High hydrogen inventory level observed after boronization maybe due to the boronization material used (C_2B_{10}H_{12}). Ion cyclotron rf conditioning is proved to be an efficient wall conditioning method for superconducting device because it could be carried out under toroidal magnetic field. In this paper, the procedure of boronization is described, and subsequently sample analysis and the effect on plasma operation are introduced. Conclusion is given at the end.

1. Introduction

EAST is the first all superconducting tokamak with a divertor configuration. The first limiter plasma was obtained in September, 2006, and the first divertor plasma was obtained in 2007. During the first plasma experimental campaign of EAST, its first wall is stainless steel except for two Molybdenum limiters. Efficient wall conditioning is needed to suppress the high-Z impurity contamination in the plasma. Boronization has been reported as one of the most effective methods for suppression of high Z impurities and oxygen [1, 2]. A simple mechanism is proposed that the thin boron film would cover the first walls and keep oxygen in the form of boron oxide [2]. These result in suppression of core plasma impurities. Different boronization materials have been used on a few devices, such as, B_2H_6 in TEXTOR [3], DIIID [4] and Alcator C-Mod [5], B(CH_3)_3 in MAST [6] and NSTX [7]. On EAST, carborane (C_2B_{10}H_{12}) is used due to its low level of toxicity and stable chemical properties. The boronization is carried out during ion cyclotron resonant frequency (ICRF) conditioning or glow discharge cleaning (GDC) with helium as support gas.

2. Experiment

The EAST’s main parameters can be found in reference [8]. In its first limiter and diverter operation, boronization has been carried out for five times, among which two times are GDC boronization and others are ICRF boronization. The EAST boronization system is shown in figure 1. For GDC boronization, two of the four GDC anodes are used. For ICRF boronization, one of the two ICRF antennae is used. Boronization system also includes one small metal box for loading carborane, and one transfer pipe for introduction of carborane vapour into the plasma vacuum vessel (PVV). During

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conditioning, helium gas is injected into the PVV through the same flange. A electrical magnetic valve is used to puff helium gas for wall conditioning in the pressure feedback control mode. For the monitoring of the process, one film thickness monitor and one sample probe are located half way between the position for gas puffing and that for pumping. There is a residual gas analyzer (RGA) installed on the differential chamber for the mass spectrum analysis.

![Figure 1. Boronization system](image1)

**Figure 1.** Boronization system

**Figure 2.** The evolution of box temperature (T) and RGA peaks corresponding to Hydrogen (H₂), Helium (He) and carborane (71).

2.1. Pre-treatment

For ICRF boronization, the rf frequency is 30 MHz. Usually 60 minutes of helium ICRF cleaning is applied in advance. The idea is that a cleaner surface is helpful for the boron film coating. The toroidal magnetic field during plasma operation is 2 Teslas, and is reduced to 1.2 Teslas for ICRF cleaning. All the four turbo-molecular pumps (TMP) are used, and Helium is puffed by the gas injection system (GIS) keeping the PVV pressure at 9.3E-3Pa. During this ICRF conditioning, the power is 8 kW, and the period is 0.3 s on and 1.2 s off. 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 120 °C.

![Figure 3. The evolution of film thickness (Thick), RGA peak corresponding to carborane (71) and temperature (T).](image2)

2.2. Boronization

This phase is started when the valve isolating the carborane box and the plasma vacuum vessel is opened. Then the box is heated gradually. Usually 10 grams 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 is pumping. During boronization, the power of ICRF wave is raised to 15 kW to enhance the decomposition of the carborane molecules. In this phase, the carborane temperature is a key issue because it greatly affects the throughput of the carborane vapour flow. In about 10 minutes the box is baked up to about 100 °C and then kept stable. Figure 2 shows the evolution of temperature and RGA signals on the differential chamber during the boronization. When the temperature of the box reaches 45 °C, it’s shown on the RGA that peak 2 (corresponding to Hydrogen molecule) starts increasing. Correspondingly peak 4 (Helium from the GIS) decreases due to the pressure feedback control. When the temperature reaches 100 °C, peaks 11, 14 and 71, which are understood as the indication of boron related elements, start increasing obviously. Figure 3 also shows the evolution of film thickness. It is observed that about two minutes after the obvious increasing of peak 71, the thickness of film begins to increase stably. This state usually lasts for about two hours, in which the box temperature is kept roughly at 100 °C. Then peak 71 begins decreasing, and the film thickness monitor shows slower film deposition. Subsequently, box temperature is raised continuously until 200 °C, when the valve controlling the carborane box is closed.

It is observed that when ICRF wave is interrupted accidentally, the film thickness monitor shows no film deposition immediately, and the deposition resumes when the application of RF wave is restored (figure 3). Corresponding to the pause of wave application, RGA shows big increase of peak 71(The signal decreases later corresponding to the closing of the valve for saving carborane). This repeatable phenomenon suggests that it is mechanism related to rf plasma instead of simple carborane vapour condensation that plays a more important role in the film deposition for the ICRF boronization.

Even after closing the carborane box, film thickness monitor show that the deposition could last for more than half an hour as long as the rf wave is applied. This could be due to the release of the carborane and its decomposed molecules adsorbed on the wall in the former stage.

2.3. Post-treatment

Based on the experience on HT-7, high H inventory level is always observed due to the large amount of H from the carborane. Therefore, after boronization the first and the most important task is to
remove H from the vessel. Helium ICRF cleaning is proved to be helpful. For enhancement of outgassing, the PFCs are kept at high temperature and all four TMPs are put into use. To limit the damage to the freshly deposited boron film on the first walls, the rf power is decreased to 5 kW.

2.4. Sample & plasma operation

2.4.1. Samples. During boronization two stainless steel (SS) samples and one silicon sample are placed in EAST via sample probe. The layout of the sample probe is shown in figure 4. It’s located inside a diagnostic duct and the radial distance between the limiter and sample probe is 601 mm. After boronization one of SS samples is withdrew, and the other samples are collected after being exposed to about 100 typical plasma discharges.

The results analyzed by the X-ray photoelectron spectroscopy (XPS) are shown in figure 5 and 6. Comparing the SS sample with fresh B film and that exposed to the plasma, it could be observed that the former has much more B content. B exists mainly in the form of B-B bond in the former sample, while mainly in the form of B-O bond for the latter. This matches the mechanism that the suppression of oxygen by boron is through the capture of O by co-deposition with B in the form of B-O bond.

2.4.2. Operation of plasma. With the help of boronization, the suppression of the high and low Z impurities is observed and the operational region of EAST device is extended, as is shown in reference [9]. After boronization, it’s feasible to have a wider current ramp-up rate (dIp/dt) range, which means higher control capability of the device. It is summarized that after boronization, dI_p/dt range for the controllable plasma operation is extended from 0.3-0.48 MA/s to 0.2- 0.62 MA/s.

3. Conclusion

Boronization has been carried out on the EAST all superconducting tokamak device for five times. Both GDC and ICRF boronization prove to be successful. For ICRF boronization, the He ICRF is carried out during pre-treatment phase. The procedure of boronization is well monitored by RGA and film thickness monitor. After boronization, He-ICRF cleaning is applied to decrease the H inventory. 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. For the plasma operation, boronization improves the wall condition and extends both the operational region and current ramp-up capability of the device effectively.

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