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Wall Conditioning with a High Magnetic Field in HT-7 Superconducting Tokamak

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Abstract

ICRF wall conditioning techniques, which includes the hydrogen removal, impurity cleaning, boronization and siliconization, were described in this paper. This new technique has been demonstrated to be very effective for wall conditioning, recycling, isotopic control and used daily during experiments. The RF plasma parameters were measured as T_e = 3~8 eV, T_i = 0.5~2 keV, n_e = 0.3~5 × 10^{17} m^{-3} by different diagnostics. The nontoxic and nonexplosive solid carborane powder was used for the RF boronization. Energetic ions cracked the carborane molecule and the boron ions impacted and deposited onto first wall. Comparing with GDC boronization, the B/C coating film shows the higher adhesion, better uniformity and longer lifetime to the plasma discharges. Siliconization was carried out by using a high field side long RF antenna, which made the discharge more uniform. The ratio of SiH_4 to helium is about 5:95 at the pressure range of P_v = 0.8~8 × 10^{-2} Pa. Compare with boronization, it showed quicker recovery from a bad wall condition due to leakage of air to good wall condition. Plasma density could be easily controlled after siliconization. But the lifetime is much shorter than that obtained by boronization. Plasma performance has been improved after RF boronization and siliconization.

Keywords:
tokamak, wall condition, boronization, siliconization, ICRF

1. Introduction

It is well known that the proper wall conditioning is essential to obtain good plasmas. With a high magnetic field, traditional wall conditioning techniques would not work. A new technique of wall conditioning, so called RF conditioning, has been tested on TORE SUPERA [1,2], TEXTOR-94 [3] and HT-7 tokamak [4,5] by injecting ion cyclotron resonant frequency (ICRF) wave into plasma.

A RF conditioning technique has been successfully applied on the HT-7 superconducting tokamak, which includes hydrogen removal, impurity reduction, recycling control, boronization and siliconization. This special technique is aiming the wall conditioning for future large superconducting tokamaks, such as ITER, in the presence of the high magnetic field. The effects of wall conditioning by applying RF plasma are demonstrated. It shows much better results than those obtained by glow discharges and Taylor discharge cleaning. The details of the technique and its application for processing different wall states are given in this paper.

2. RF Plasma and Parameters

The theory of plasma production in tokamaks using RF in the ICRF range has been investigated by some authors [6,7]. To initiate the discharge, an antenna has to

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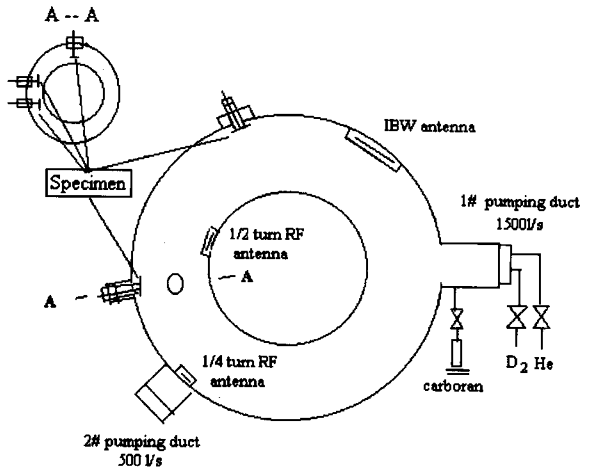

Fig.1 The set-up of RF conditioning system on HT-7

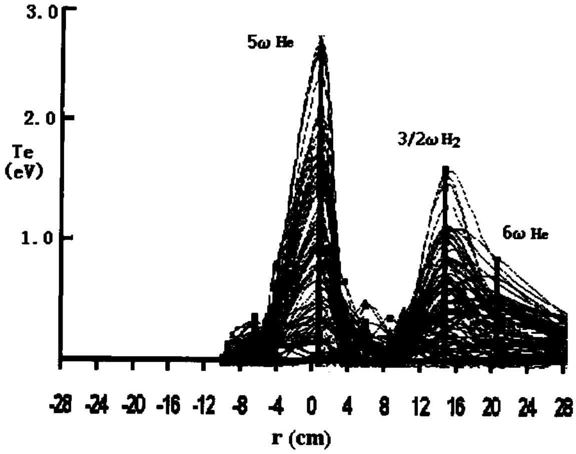

Fig. 2 Electron temperature profile measured by ECE. B_T = 1.5 T, $P = 4 \times 10^{-2}$ Pa, P_{RF} = 25 kW, f = 30 MHz.

generate a RF electric field $E_{||}$ parallel to the magnetic field lines. The $E_{||}$ at the antenna is responsible for neutral gas ionization by highly accelerated electrons during gas breakdown. To get a higher ionization ratio, the harmonic resonance absorption layers should be inside the plasma. The ion cyclotron frequency ω is qB/m. Where B is the magnetic field, q the ionic charge and m the mass. The RF antenna for heating can give a certain $E_{||}$, which is also suitable for plasma production.

The hardware set-up for the RF conditioning is the same as ICRF heating. Three kinds of RF antenna configurations are used. A 1/4-turn antenna with Faraday shielding is installed in the low field side of the torus. A 1/2 turn long antenna is mounted in the high field side. An ion Bernstein wave (IBW) antenna is set in the mid-plane of low field side. The arrangement of whole system is shown as Fig. 1.

RF plasma is easily produced by injection of the ICRF power in the range from 5 kw to 50 kw for both helium and deuterium working gas. Toroidal field (0.1 ~ 2.5 T), gas pressure (8×10^{-4} Pa ~ 5×10^{-1} Pa) and radio frequency (RF) (24 ~ 30 MHz) have been scanned to optimize the cleaning efficiency. The basic RF plasma parameters produced by different antenna configurations are measured by a few diagnostics. Quadruple mass spectrometer (QMS) analysis during and after the RF conditioning is carried out. Electron temperature is estimated from visible line spectrum, Langmuir probe and ECE. The difference of electron temperature by these diagnostics is within a factor of three. Electron temperature is in the range 3 eV ~ 10 eV within an injection power of 35 kW. The electron temperature for helium RF plasmas is higher than that in deuterium plasmas by a factor of two with the same discharge condition. Electron density is in the range of 0.5–3 × 10^{17} m^{-3}, which is measured by HCN interferometer and Langmuir probe. Ion temperature is as high as 0.5–2 keV with high-energy tail of a few tens of keV.

Since the presence of the harmonic resonant layers of the different particles, which are visible inside of the plasma, electron temperature and density are not uniform across the minor radius. Figure 2 shows the T_e profile with an injection power of 25 kW. The maximum T_e is about 3 eV at the 5th harmonic layer of helium. A few other resonant layers also appear where local T_e is higher than the non-resonant regions. Central ion temperature is about 1 keV. With the injecting RF power increases, T_e increases a little and T_i increases linearly with the RF power. With a higher filling pressure and RF power, the T_e profile becomes flat without clear peaks. Compare with the plasma property of GDC, electron temperature is similar but ion temperature is much higher. Energetic ions are produced by RF plasma, which is expected to be produced in the resonant layer regions.

3. Particle Removal

As we know, two effects which govern the conditioning efficiency are outgassing rate of particles from the wall and the ionization rate of desorbed molecules which induces a redeposition. For getting higher outgassing rate, a higher particle flux to the wall with suitable energy is favorable. For reducing ionization rate, the pulsed-RF-mode with 0.3s RF power and 1.5s time interval is used. Helium RF discharge is used mainly for hydrogen removing. It is also very effective for the replacement of deuterium (and its isotopes). This makes plasma start up very easy and results in particle recycling being controllable manner. The pulsed mode with higher filling pressure (0.05~0.1 Pa) increases the conditioning efficiency by controlling electron density and temperature separately to minimize the hydrogen redeposition probability. The partial pressure of hydrogen was increased by two order of magnitudes after RF plasma was initiated, which mainly comes from the desorption from the wall. High hydrogen removal rates have been obtained.

The RF injection power level plays a very important role in the helium RF wall conditioning experiment. In the lower power level (i.e. the power is lower than 20 kW), the hydrogen removal rate goes up quickly and reaches a saturation status when P_{RF} is great than 30 kW. For effectively removing the impurities, such as CO, CO_2 and H_2O, different optimized RF powers are needed. The impurity removal is due to the bombarding of neutral energetic particles to the first wall. An increase of filling pressure increases the plasma density and induced a reduction of electron temperature. Higher plasma density (high filling pressure) improves cleaning efficiency.

Deuterium ICRF discharge is used for surface cleaning and wall isotope control. The pulsed mode with optimized pressure of 1×10^{-1} Pa is used. The electron temperature is lower (2~3 eV) compared with helium discharge. Electron temperature changes a little within the injection RF power of 30 kw. The low temperature minimizes the strong plasma reionization and wall redeposition of neutral species. High temperature deuterium ion and its energetic tail are observed. Both

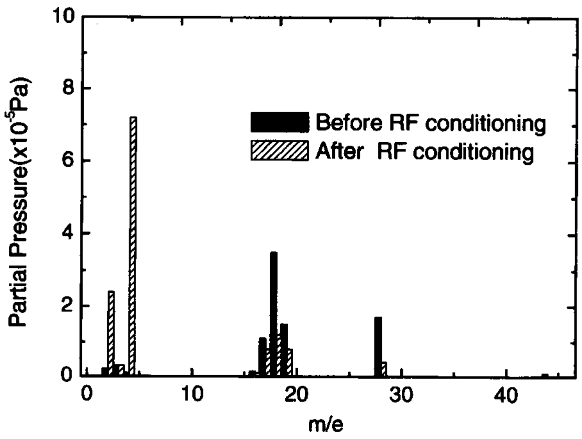

Fig. 3 QMS data before and after D_2 RF wall conditioning. B_T = 1.5T, f = 30 MHz, P_v = 0.15 Pa.

energetic and reactive particles bombard the first wall and induce the desorption of molecular impurities. These are main reasons for the good conditioning efficiency of the deuterium RF discharge. QMS data in Fig. 3 shows the results before ICRF wall conditioning and 30 minutes pumping after 60 minutes pulsed 15 kW RF discharge. After ICRF wall conditioning, CO reduced by a factor of three and H_2O reduced more than two times, while the working gas (H_2 and D_2) part increased significantly, which was greater than 80% of total pressure. Very effective impurity cleaning capability was demonstrated.

Three years data shows that, comparing with GDC with similar parameters in HT-7, the hydrogen removing by RF cleaning is 20 time higher and particle-removing rates to H_2O and CO is more than two order of magnitudes. The difference is due to the different plasma properties. Very high ion temperature of RF plasma may play key role to obtain high cleaning efficiency. The energy of the neutral flux, which induced by charge-exchange with energetic ions, is much higher than that of GDC, which results in is more effective desorption of the impurity from the wall.

4. RF Boronization

The nontoxic and nonexplosive solid substance carborane ($C_2B_{10}H_{12}$) was chosen for the boronization material for easy handling and exhausting [7]. According to the laboratory results from reference [8], the liner temperature was set around 150 ~ 200°C. The wall was baked to 100°C. Toroidal magnetic field was about 1.8 T and the RF frequency was 30 MHz. With this arrangement, the fundamental hydrogen resonant layer is located inside of the plasma.

12 rectangular samples of 10 mm × 10 mm dimension with different materials (graphite, stainless steal) were put into the different places of the machine before boronization with same radius of liner. The carborane container was heated and kept at 60°C. A stable partial pressure of 0.2 Pa was provided. Helium gas was regulated to the ratio of He: Caborane of 1:1. To improve toroidal uniformity of the coating, the pulsed RF power of 10 kW was coupled to the plasma with 2.4 seconds power on and 2 seconds power off. Plasma color was gradually changed from the light green to the pink, which indicated the injection of carborane vapor. Since several different species of particle existed in the plasma, their harmonic cyclotron resonant layers were clearly observed from the RF plasma, which was produced by the short 1/4 turn

antenna. As the injection of the carborane vapor and stable RF discharge continued, the helium gas filling was gradually reduced to the zero, which is favorable to get higher boron deposition rate.

Carborane of 4 grams was used and the boronization process lasted for 65 minutes. The carborane container was heated up to 120°C at the end to evaporate all the carborane. After that, all the pump ducts were fully open. Helium RF plasma restarted and continued for 20 minutes but the RF power was reduced to 3 kW to pre vent the heavy bombardment to the fresh boron film. The purpose for the helium RF conditioning after boronization was to remove the huge hydrogen content that was absorbed in the film during the boronization.

The residual gas analysis (RGA) was done during boronization with RF plasma. The results showed a different pattern with boronization using GDC on HT-7 and other devices. The group of mass 144($C_2B_{10}H_{12}$) was the only peak masses detected during GDC boronization in HT-7. The highest amplitude was given with mass numbers 2 and 4 while very small amplitudes of mass 18 and 44 were also observed during helium RF clearing. The RGA pattern of the RF boronization is shown in Fig. 4. The partial pressure for the mass 11 and the groups of 22 were 50 times higher than that of mass 144. This means that the carborane molecule is cracked into smaller pieces by the bombardment of high-energy ions of RF plasma.

X-Ray-induced photoelectron spectroscopy (XPS) was used to analyze the film properties of the specimens. Some of them were taken out after boronization. The other remained inside machine and exposed to the plasma discharge. XPS shows that boronization produces a fine amorphous boron-carbon films (a-C/B:H). Boron layer has a well-defined composition, which is homogeneous in depth, as can be seen from the depth profile of graphite specimen shown in Fig. 5. B/C ratio is about 3 up to a depth of 220 nm for the fresh film shown in Fig. 5 (a). The oxygen concentration is about 10% since the presence of H_2O and CO during the film deposition. This is because of the continuous gettering of oxygen in the growing of the film during the plasma bombardment.

The prime advantage of boronization films is their ability to getter oxygen due to the incorporated boron atoms and their superior resistance to chemical erosion by thermal and energetic hydrogen species. The oxygen gettering was observed when the film was exposed the bombardment of plasma discharge shown in Fig. 5 (b). Oxygen content increases from 10% to 25% and boron content decreases from 60% to 50% after 250 shots. This demonstrates that boron film has very strong oxygen capture capacity. The thickness of the film was reduced about 80 nm after 250 shots.

Since the anisotropy of RF discharge during the first boronization, which was indicated by the ion cyclotron resonant layers, the film thickness capability along the poloidal direction must not be uniform. The film uniformity was not measured by the limitation of the windows during the first boronization. The uniformity along the poloidal direction was measured with specimens on the top and horizontal windows

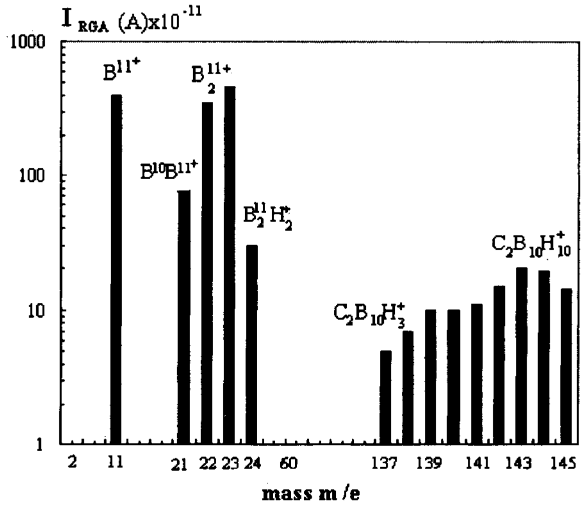

Fig. 4 The residential gas analysis during ICRF boronization. B_T = 1.8 T, P_{RF} = 10 kW, f = 30 MHz

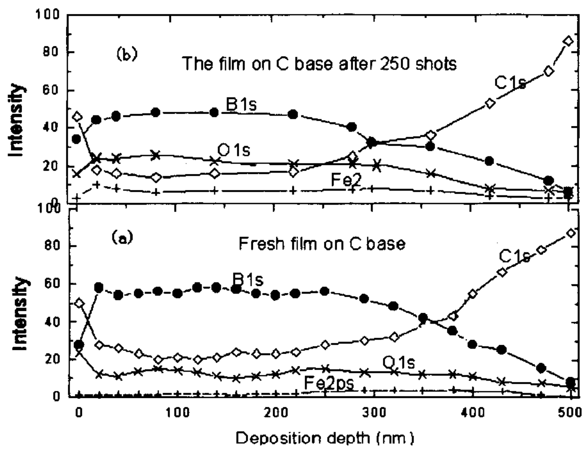

Fig. 5 XPS analysis of boron film for the graphite specimen (a) fresh film (b) film after 250 shots

during next campaign. The film thickness along the poloidal direction is different by the low field side antenna. The long antenna was used. The RF plasma produced by long high field antenna was nearly homogeneous along the both toroidal and poloidal directions. Clear separation in ion cyclotron resonant layers could not be observed during RF plasma discharge. The film thickness of top window specimen was about 20 nm thinner than those from the horizontal window, which was less than 10% of the film thickness. The uniformity along the poloidal direction was dramatically improved.

The plasma performance was immediately improved after RF boronization. The metal impurity lines were disappeared. The visible line of carbon and oxygen were reduced by a factor of three. The radiation power significantly dropped from 80% of input power to the level of 16% on the condition of same plasma current and density. The Z_{eff} dropped close to the unity at the density 5×10^{19} m^{-3}. Wider Hugill stability operation region was observed. The effect of boronization was still remained after 1500 shots, which was indicated by the decrease of Z_{eff}, loop voltage and impurity radiation. Generally speaking, the lifetime of file with 4g carborane is about 1500 shots.

5. RF Siliconization

Siliconization was carried out by using high field side long RF antenna, which made the discharge more uniform. The ratio of SiH_4 to He is about 5:95 at the pressure range of $P_v = 0.8\sim2 \times 10^{-2}$ Pa for the safety handling the exhausting silane gas from pumping system. Pulsed mode was used with one-second power on and one-second power off. The RF power was 10 kW and the pre-cleaning was not needed. The whole procedure last normally for about 30 to 60 minutes. Plasma discharge was fired after siliconization without post helium RF cleaning to reduce the hydrogen content in the film. Very good plasma discharges were immediately obtained. But lifetime of the silicon film was very short, which lasted for about 50 shots since the thickness of the film is only about 20~30 nm.

Higher silane to helium ratio (10:90) and filling pressure (0.05~0.2 Pa) were used in the following RF-siliconization. The lifetime increased by a factor of five. The thickness of the film was about 60 nm. It showed bright interference colors indicating their semi-transparency. The Si/C ratio is around 1~2. Silicon mainly bonds with carbon. After exposing to tokamak discharges, Si-O bond increased by a factor of three, a higher efficiency in gettering oxygen of a-Si:H films was observed than that of a-C/B:H film. Silicon layer has a well define composition, which is homogeneous, amorphous and uniform both in depth and toroidal directions shown as in Fig. 6.

Plasma performance quickly improved after each siliconization. Lower q_a and wider stable operation region were achieved compared with RF boronization. Higher electron temperature was obtained for the same plasma current and density in tokamak discharge. Impurity evolution shot by shot after siliconization gave good results. Oxygen content dropped by a factor of two after siliconization and gradually recover after 100 shots, while carbon radiation reduced by more than three time and kept at very low level even after 300 shots. XPS analysis to the bombarded film showed that a large amount of SiC was formed. Silicon radiation increased by a factor of 2.5. A weak hollow and wider density and electron temperature profiles were formed after siliconization. The edge safety factor could be as low as 2.45. The total radiation loss was reduced.

Compared with boronization, siliconization takes much short time. It shows much fast recovery after a serious degradation of the condition due to leakage of air to good wall condition. It takes only one hour after a minor leakage of the air. Plasma performance was back to a good state. The density can be easily controlled after siliconization without the need of further helium RF conditioning needed for reducing hydrogen content in the film. But the lifetime is shorter than that obtained by boronization due to thinner film (60 nm) compared with boron film (300 nm). Metal reduction gradually recovered after 120 shots and oxygen reduction effects

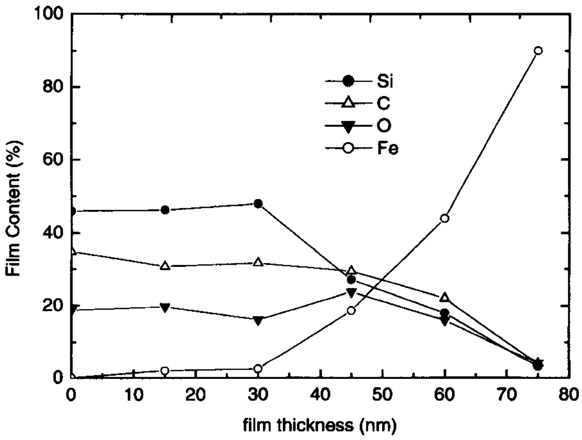

Fig. 6 XPS analysis of silicon film for the fresh stainless steal specimen.

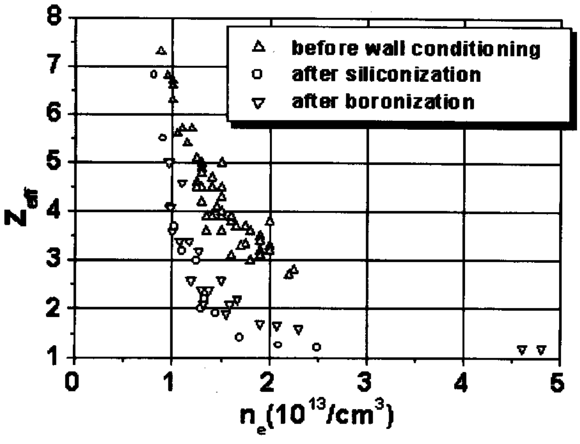

Fig. 7 Comparison of impurity after the different wall coatings.

lasted for about 100 shots, while boron film lasted for nearly 800 shots. If longer preparation of siliconization and the same thickness of the film were obtained, the lifetime of silicon film would increase. But it seems that the silicon coating with same thickness as boron one (300 nm) could not last for more than 500 shots. Further experiments will be carried out in future to compare the lifetime of two kind films with the same thickness. The uniformity of the film is as good as boron one. The main reason for much thinner silicon film is due to the high ratio of helium to silane gas. The reduction of the impurity radiation of siliconization is not as good as boronization at the low-density case. Fig. 7 shows a quantitative compare of impurity reduction with density. When the density is higher than 2×10^{19} m^{-3}, the reduction of the impurity is almost same. Plasma performance was improved by either RF-boronization or RF-siliconization.

6. Summery

RF wall conditioning technique has been tested, developed and routinely used in HT-7 tokamak. This technique is aiming future large superconducting devices in the presence of high magnetic field. Comparing with GDC and TDC, the hydrogen-removal rate increased by a factor of 20 and cleaning efficiency to impurity is as high as two order of magnitudes. Basic plasma parameters produced by different antenna configuration and their role to get best cleaning and coating effects were studied. High cleaning efficiency is attribute to the very high ion temperature, which induces the high-energy neutral flux to the first wall and easily desorbs the impurities. RF boronization and siliconization were carried out. The B/C:H and Si/C:H films show the high adhesion, uniformity and longer lifetime to the plasma discharges than those obtained by normal GDC method. The impurity level dropped day by day by the different RF procedures. Plasma performance has been improved after RF boronization and siliconization. Higher lower hybrid wave current driven and ICRF heating efficiency were obtained after RF boronization. This new technique shows that it is very effective and powerful for the quick and real-time wall condition for future large superconducting magnetic fusion devices.

References

[1] E. Gauthier *et al.*, J. Nucl. Mater. 241-243, 553 (1997).
[2] E. De La Cal, E. Gauthier, Plasma Phys. Contol. Fus. **39**, 1083 (1997).
[3] H.G. Esser *et al.*, J. Nucl. Mater. 241-243, 861 (1997).
[4] Y.P. Zhao, Chin. Phy. Lett. **14**, 916 (1997).
[5] J. Li *et al.*, Nucl. Fusion **39**, 973 (1999).
[6] A.I. Lyssoivan *et al.*, Nucl. Fusion **32**, 1361 (1992).
[7] M.D. Carter *et al.*, Nucl. Fusion **30**, 723 (1990).
[8] M. Yamage *et al.*, Jpn. J. Appl. Phys. **32**, 3968 (1993).