J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 320–323

ICRF Boronization on HT-7 Superconducting Tokamak

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(Received: 18 January 2000 / Accepted: 23 June 2000)

Abstract

Ion Cyclotron Resonance of Frequencies (ICRF) boronization has been successfully tested on HT-7 Superconducting Tokamak, which is the first try on tokamak. The new technique has demonstrated itself a highly efficient, fast and easily controllable method for the future large device, especially for the superconducting tokamak. The nontoxic and non-explosive carborane powder was used as boronization material. The pulsed RF plasma was produced by 20 kW ICRF generator. High- energy particles cracked the carborane molecules and the ions hit and penetrated deep into the first wall. Comparing to the previous boronization by helium glow discharge cleaning, ICRF boronization shows much better film properties, such as higher ratio of boron to carbon, better uniformity of the film and longer lifetime. Plasma performance has been improved after boronization. The new technique could be used for in-time control of wall conditioning for long pulse length of plasma discharge on large tokamak between shots.

Keywords:

wall conditioning, ICRF boronization, superconducting tokamak

1. Introduction

The first wall coating in fusion devices plays an important role in reducing plasma impurities and hydrogen recycling [1,2]. Because of the high permanent magnetic field in the superconducting tokamak, the conventional glow discharge cleaning (GDC) cannot be used between shots. Therefore, a new method applied to the high continuous superconducting magnetic field must be developed for efficient conditioning. The plasma performance is directly related to the wall condition (such as low Z_{eff} operation or H-mode accessibility), a new efficient real time wall coating technique also needs to be developed. In our laboratory there is an ICRF generator and antenna system. Making use of the generator and antenna system, a new technique for wall conditioning with a permanent magnetic field has been successfully developed on the HT-7 superconducting tokamak [3] and other devices [4] by ion cyclotron resonant frequency (ICRF) wave injection and very good results have been achieved.

Boronization on the HT-7 superconducting tokamak using carborane ($C_2B_{10}H_{12}$) by ICRF wave is described in this paper. A direct result of this surface modification shows that the impurity content is substantially reduced, particularly oxygen containing gases, such as carbon monoxide, water, and that Z_{eff} decreased by a factor of 3 during post-boronization plasma discharge.

2. Boronization Process on HT-7 Tokamak

The purpose of boronization on HT-7 superconducting tokamak is to reduce oxygen, carbon content

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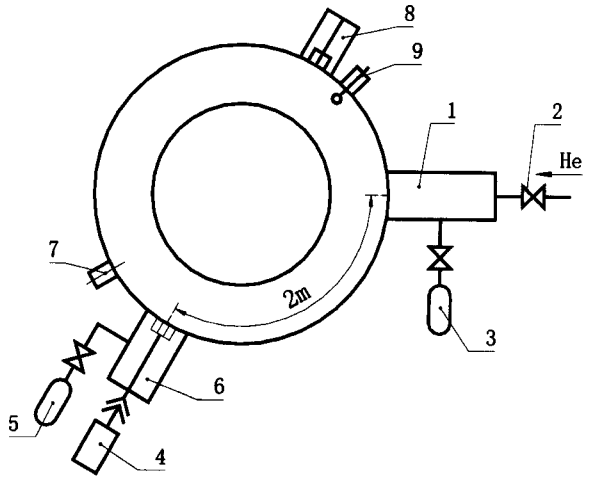

Fig. 1 Set up of the boronization system on HT-7
1-No.1 pumping duct 2-He inlet valve
3-carborane container 4,8-ICRF antenna
5-mass spectrometer 6-No.2 pumping duct
7-surface probe 9-GDC electrode

and cover all plasma facing surface with a low Z film. HT-7 is a middle sized iron core superconducting tokamak in 24-hour operation with molybdenum limiter configuration. The main parameters of HT-7 are: R = 1.22 m, a = 0.285 m, (vacuum chamber volume of about 4 m^3,) The effective pumping speed of the torus is about 1 m^3s^{-1} for N_2. I_p = 100 ~ 250 kA, n_e = 1 ~ 6 × 10^{19} m^{-3}, T_e = 600 ~ 1200 eV, T_i = 300 ~ 800 eV, B_T = 1 ~ 2.2 T. The plasma-facing surface on HT-7 mainly consists of stainless steel and molybdenum (limiter). The HT-7 boronization system is shown in Fig. 1. A gas injection port and a stainless steel reservoir in which the nontoxic and non-explosive solid carborane ($C_2B_{10}H_{12}$) was filled were installed on the first pumping duct. The RF antenna and a residual gas analysis (RGA) system with differential pump were installed on the second pumping duct. The RGA is located 2 m toroidally from gas inlet. A movable probe for surface analysis is located 0.4 m toroidally from RF antenna. Boronization using carborane has been carried out more than 20 times since 1998.

The carborane vapor was injected through a port 150° toroidally away from the RF antenna. The main pumping duct was located at the same port with the RF antenna. In order to get the best boron film coating results, wide range parameters have been scanned, such as toroidal field (1.0 ~ 2.0 T), gas pressure (5 × 10^{-3} ~ 3 × 10^{-1} Pa), RF launch power (15 ~ 28 kW). The procedures were carried out as follows. The RF (7–10 kW) cleaning for 1–2 hours has been done with helium to remove the impurity on the first wall before ICRF boronization, which was also very useful to get better adhesion of the film. The liner and pumping ducts were baked to 185°C and the wall temperature was about 80 ~ 120°C. After that, the carborane container was heated to 80°C to maintain the stable gas filling and RF discharge. All the pump valves were opened partially which gave little pumping. The pressure was 5 × 10^{-2} Pa with the mixture of helium to carborane 1:1. After stable RF discharge was established, the He gas filling was gradually reduced until it was fully closed. To improve toroidal uniformity, the pulsed RF power of 20 kW was coupled to the plasma with power on for 0.3 s and off for 1.3 s. The frequency of the RF wave was 30 MHz and the toroidal magnetic field was 1.8 T.

The RF plasma parameters were measured by different diagnostics. The electron temperature measured by visible spectroscopy was a few electron-volts. Plasma density was about 1 × 10^{17} m^{-3}, and the hydrogen ion temperature measured by a neutral particle analyzer was 2 keV with a high-energy tail up to a few tens of keV. The ion temperature is a very important parameter since it governs the energy of boron ion that impacts the wall. The residual gas analysis (RGA) with differential pumping system was done during ICRF boronization. The results showed a different pattern from boronization using glow discharge cleaning (GDC) on HT-7 and other devices [5-7]. The group of mass 144 ($C_2B_{10}H_{12}$) was the only peak masses detected during GDC boronization on HT-7. However, during helium RF boronization the highest mass numbers were 2 and 4 while very small amplitudes of mass 18 and 44 were also observed. The mass spectrum pattern during ICRF boronization is shown in Fig. 2. The partial pressure for the mass 11 and the group of 22 were 50 times higher than that of mass 144. This means that the carborane molecule is cracked into smaller pieces. Two grams carborane was used each time and the boronization process lasted for 2 hours. The carborane container was heated up to 120°C at last to evaporate all the carborane. Then all the pump gate valves were fully open. Helium RF plasma with power of 5–7kW was continued for 1 hour to prevent the heavy bombardment to the fresh boron film and to remove the content of hydrogen absorbed in the film during the boronization. The RGA results after boronization showed that the partial pressures of oxygen containing gases (H_2O, CO, CO_2) were all reduced by one order. In winter 1998, plasma operation in HT-7 lasted one month all around the clock.

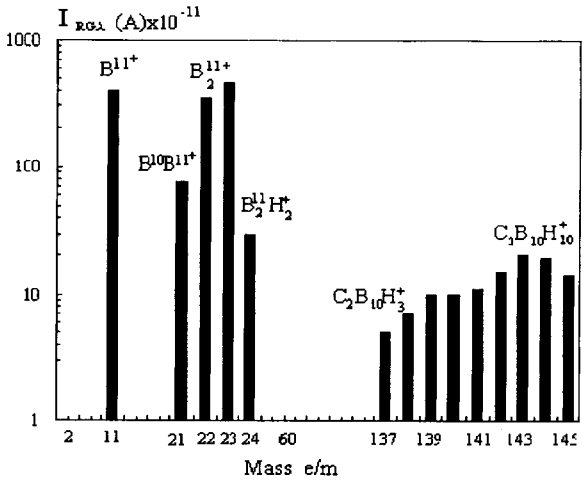

Fig. 2 The residual gas analysis during ICRF boronization:
B_T = 1.8 T, P_{RF} = 10 kW, f = 30 MHz, $P = 3 \times 10^{-1}$ Pa.

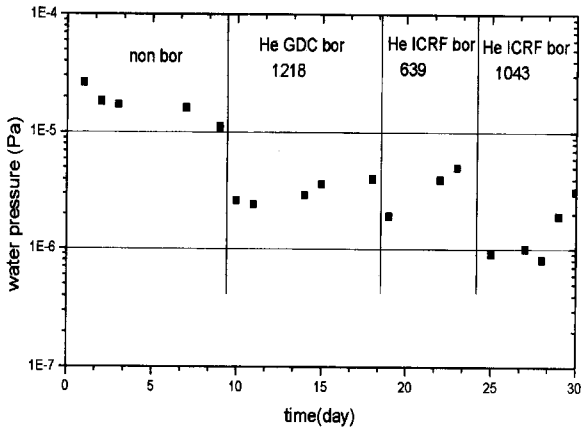

Fig. 3 Long term trend of H_2O partial pressure in plasma discharge without boronization and boronization (GDC, ICRF).

A long-term trend of water partial pressure in plasma discharge with and without boronization (GDC, ICRF) is shown in Fig. 3. Water partial pressure after GDC boronization was reduced by one order. After ICRF boronization the water partial pressure was further reduced, but gradually increased in the course of 639 shots of plasma discharge. Then ICRF boronization was once again carried out, the water partial pressure was substantially reduced by two order compared to that of the non-boronization condition. Water partial pressure was not significantly increased until 1043 shots of plasma discharge.

The sample analysis by X-ray photoelectron

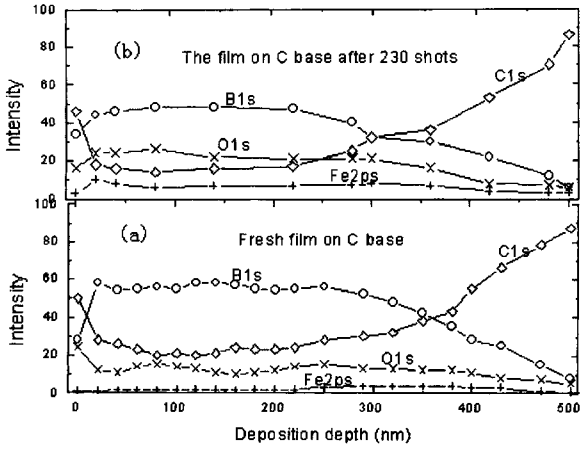

Fig. 4 The boron film property for the fresh film (a) and the film after 230 shots (b).

spectroscopy (XPS) was done to study the stability of the film with plasma discharges. Analysis of B/C coating showed that it consisted of a fine amorphous C/B: H film. The film shows very strong adhesion to the first wall. The measured thickness of the film *ne*ar the pump duct was only one third of that in the gas inlet zone on HT-7. The distribution of the film along the toroidal direction by RF boronization is *ne*arly uniform, measured by two samples in the opposite positions along toroidal direction. Even after 250 shots with ICRF and LHCD (about 400 kW RF power totally), 11 of the total samples showed *ne*arly the same structure with fresh films except for thickness. Only one sample had the clear damage spots, which might be bombarded by the energetic electron and ions during plasma discharge.

Since the properties of all the sample films were almost the same by film analysis, we only presented the results of the graphite sample here. The B/C ratio varied from 2.8 to 3 for a depth of 250 nm. The depth distribution for all the elements (B, C, O, and Fe) was uniform for the depth up to 250 nm. Fig. 4 (a) shows one important and unique feature. There is no clear boundary of the B/C film on the graphite base (also true to other materials). The boron contents could be detected up to a depth of 500 nm, which is well beyond the coating depth. This means that the high-energy boron ions (also other kinds of ions) hit the wall and penetrate into the base materials and deposit into the first wall. The film thickness of the coating is about 240 ~ 320 nm. Since the limitation of the windows, the uniformity of the film along the full poloidal direction was not checked. It is hard to tell the poloidal

uniformity. More work *ne*eds to be done on this topic in the near future.

Fig. 4b shows that oxygen content increases from 15% to 26% and boron content decreases from 60% to 50% after 230 shots. This demonstrates that boron film has very strong oxygen capturing capacity. The thickness of the film was reduced about 80nm after 230 shots. The following 1500 shots were of higher density ($2 \sim 5 \times 10^{13}$ cm^{-3}) with less energetic particles, which made the bombardment to the film less serious than the first 250 shots. The loop voltage and the Z_{eff} were gradually approached the non-boronized wall condition. In general, the lifetime of the coating is 2000 shots.

Conventional ohmic discharges were carried out after the boronization. Impurity contamination was almost the same as that of other successfully boronized device. The remarkable feature of the ICRF boronization was the fast transition of the device condition from the unconditioned state to the very low impurity level. All the procedures took only a few hours. Loop voltage dropped dramatically and the Z_{eff} changed from 4 to a value close to 2 at the line average density of 1.5×10^{19} m^{-3} and close to 1 at higher density ($4 \sim 5 \times 10^{19}$ m^{-3}). The total radiation power dropped sharply to the level of 10% ~ 18% of ohmic power, which usually is 50 ~ 90% without boronization.

In the evening of December 28,1999,ICRF boronization was carried out, in the morning of December 30, plasma discharge duration of 10.71 seconds was reached in conventional ohmic discharge.

3. Conclusion

ICRF boronization has been successfully developed for the first time on tokamak. This new technique has demonstrated to be a highly efficient, fast and easily controllable procedure for the future large tokamak. The high-energy ions and the ICRF plasma make the film highly adhesive, amorphous, with a deep penetration depth, uniform both in thickness and the toroidal directions. Comparing with the conventional boronization method on HT-7, it shows much better film properties, such as high ratio of boron to carbon, longer lifetime and better uniformity. Its influence to plasma performance gives better results. This special technique could be efficiently used as a routine method of wall conditioning for future larger devices and eventually for the superconducting reactor.

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