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Boronization effects using deuterated-decaborane ($B_{10}D_{14}$) in JT-60U

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Abstract

Boronization effects have been systematically investigated using discharges with identical conditions in JT-60U. In ~50 shots after boronization using 70 g of $B_{10}D_{14}$, the carbon content decreased due to suppression of the chemical sputtering of carbon tiles while the boron content increased. In contrast to the boron and carbon contents, the oxygen content gradually increased from ~0.7% to ~1.3% in ~500 shots. Continual boronization using 10–20 g of $B_{10}D_{14}$ every ~200 shots successfully kept the oxygen content less than ~1.0%. However, the durability of boronization using 20 g of $B_{10}D_{14}$ is much shorter than that of boronization using 70 g after vacuum vessel ventilation. Due to the reduction of the carbon and oxygen contents, Z_{eff} in 50 shots after boronization lies in the lowest range of the database.

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1. Introduction

Wall conditioning is one of keys to obtain high performance plasmas in nuclear fusion experimental devices. Boronization is one of the most effective methods in suppression of oxygen release from the walls. A thin boron film produced by boronization covers first walls and keeps oxygen in the form of boron oxide [1], resulting in suppression of core plasma dilution. In addition, the boron film also works as a reservoir of plasma particles, and helps to reduce particle recycling from the divertor plates and the first walls [2]. Boronization using different boron compounds, B_2H_6 in TEXTOR [3], DIII-D [4] and Alcator C-Mod [5] and $B(CH_3)_3$ in MAST [6] and NSTX [7] was found to have similar effects.

In JT-60, boronization using hydride-decaborane ($B_{10}H_{14}$) by a glow discharge under a helium support gas was performed to reduce oxygen impurity and particle recycling [8]. Advantages of boronization using decaborane are that decaborane does not include any carbon atoms and is less toxic than diborane and solid at room temperature, leading to easy handling. A problem of the boronization was that hydrogen originating from hydride-decaborane diluted core deuterium plasmas. About 100 deuterium tokamak discharges were required to exchange the hydrogen in the boron film to the deuterium.

For the purpose of reduction of the hydrogen in the boron film, boronization using hydride-decaborane was performed by a glow discharge under the support gas with a mixture of He and D_2 (40:60) [9]. Then, the content of hydrogen (H/H + D) in the boron film was suppressed at a level of less than 20%. However, it was difficult to maintain the glow discharge steadily during boronization session because of a CD_4 production by a chemical sputtering at the carbon tiles. As a result, the boronization session took ~4 days.

In 2000, boronization using deuterated-decaborane ($B_{10}D_{14}$) was introduced to reduce the number of conditioning tokamak discharges for removal of the hydrogen and to suppress the CD_4 production [10]. Since

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then, boronization has been performed more frequently (every 200–300 tokamak experimental discharges) because few conditioning tokamak discharges are required and a boronization session takes only one night.

In this work, about 100 discharges with identical conditions were repeated and a database was built up in order to investigate the reduction of the core impurity content and the durability of the effects of boronization systematically.

2. Experimental

Boronization was performed using a glow discharge with a mixture of helium (99%) and decaborane vapor (1%) at a baking temperature of ~520 K. To produce a toroidally uniform boron film, 12 gas inlets for the mixture gas were positioned at even intervals along the toroidal direction and 3 electrodes for the glow discharge were used. The composition of the produced boron film was close to B_4C [10]. Although the ratio of hydrogen isotopes to boron and carbon ($(H+D)/(B+C)$) is scheduled to be measured in the case of boronization using $B_{10}D_{14}$, it was about 30% in the case of boronization using $B_{10}H_{14}$ [9].

In order to investigate the durability of the boronization effects systematically, a discharge with identical conditions (the plasma current 1.5 MA and the toroidal field 3.0 T) was repeated before and after boronization. Fig. 1(a) shows a poloidal cross-section of the plasma. The plasma shape was configured to suppress local strong plasma–wall interactions except for the strike points on the divertor plates. Fig. 1(b) shows waveforms of the discharge, in which 3 periods, an Ohmic heating (OH) period without any additional heating power, an L- and H-mode periods with a neutral beam heating power of ~4.3 MW and ~13 MW, respectively, were investigated. The line-averaged electron density was set by a feed back control system at 1.2×10^{19}, 1.5×10^{19} and 2.5×10^{19} m^{-3}, in the OH, L- and H-mode periods, respectively.

The plasma effective charge (Z_{eff}) was evaluated from visible bremsstrahlung emission [11]. A VUV spectrometer [12] measured spectral lines with a transition of $n = 1$–2 of hydrogen-like boron (B V), carbon (C VI) and oxygen (O VIII). The impurity contents of boron (n_B/n_e), carbon (n_C/n_e) and oxygen (n_O/n_e) were determined from Z_{eff} and the intensity ratio of the above spectral lines. The impurity contents were confirmed with those determined from the emission intensities of C VI ($n = 7$–8) and O VIII ($n = 9$–10) lines from the core plasma by charge exchange recombination spectroscopy [13]. Fig. 1(a) also shows viewing chords and spatial points of these diagnostics. In addition, a visible spectrometer for the divertor [14] measured C II spectral line and CD spectral band, and Langmuir probes measured the electron temperature and the electron density at the strike points and the ion flux to the divertor plates.

3. Results and discussion

Fig. 2 shows the core contents of boron, carbon and oxygen in the L-mode period as a function of shot number around 12th boronization. Although the boron content became high after the boronization, it decreased

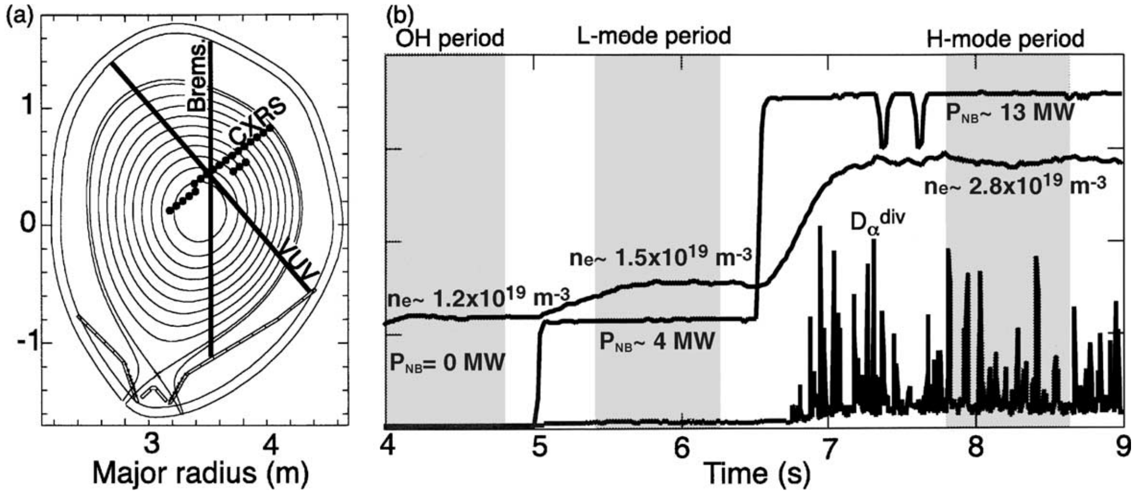

Fig. 1. (a) The plasma magnetic configuration, viewing chords of bremsstrahlung measurement and a VUV spectrometer and spatial points of charge exchange recombination spectroscopy. (b) Waveforms of a neutral beam heating power, a line-averaged electron density and D_α emission intensity from the divertor. About 100 discharges with the above condtions were repeated to build up the database.

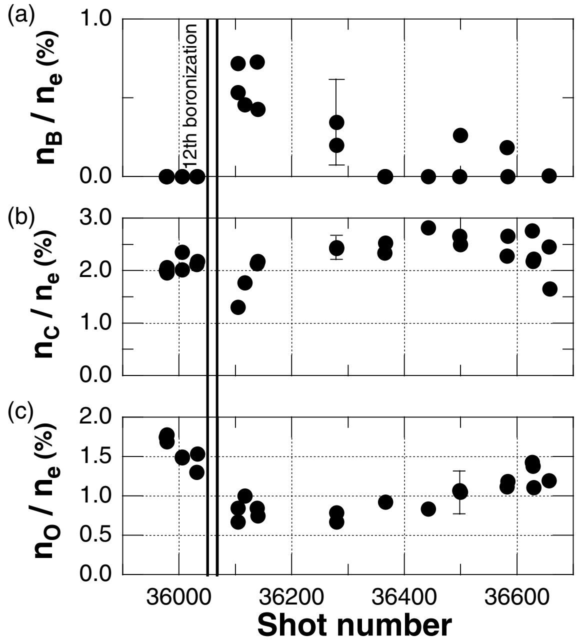

Fig. 2. The impurity content of (a) boron, (b) carbon and (c) oxygen in the L-mode period as a function of shot number around 12th boronization.

to ~0.5% in ~50 shots, and it seemed to decrease gradually to ~0%.

The carbon content was almost constant (~2.5%) except for that in ~50 shots after the boronization. In the shot range (in ~50 shots after the boronization), the carbon content was low while the boron content was high. This is considered to be due to sputtering of the boron film instead of the carbon tiles [15]. Fig. 3(a) shows the chemical sputtering yield measured at the divertor plates, where the sputtering yield is defined as the intensity of CD spectral band divided by the ion flux to the divertor plates. At the sprike point in the L-mode period, the electron temperature and the electron density were not so low and high (~40 eV and ~ 1×10^{19} m^{-3}, respectively) that heavy hydrocarbons (C_xH_y, $x \geqslant 2$) were not necessary to be taken into account [14]. The sputtering yield in the shot range was lower than that in the other shot range by a factor of ~5. Furthermore, the ionization flux from C^+ to C^{++} was also low in the shot range as shown in Fig. 3(b). The C II brightness can be referred as the ionization flux from C^+ to C^{++} on the assumption that the electron temperature and the electron density at the strike point are constant amongst the discharges in the database because of the identical discharge conditions.

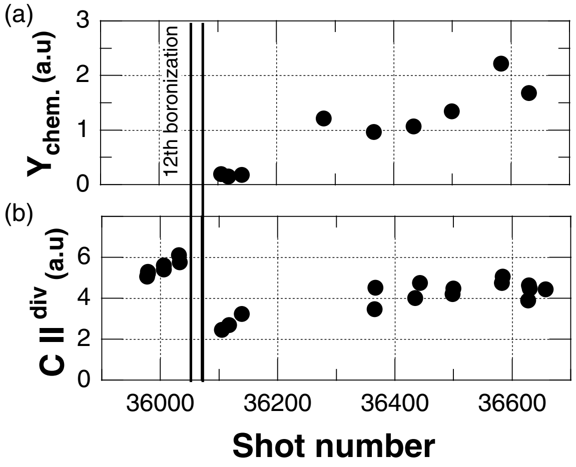

Fig. 3. (a) The chemical sputtering yield at the divertor plate and (b) the C II brightness from the divertor plasmas as a function of shot number around 12th boronization.

In contrast to the boron and carbon contents, the oxygen content gradually increased from ~0.7% to ~1.3% in ~500 shots after it decreased by the boronization as shown in Fig. 2(c). The oxygen content less than ~1% in the L-mode period was kept for ~400 shots. The trace of the oxygen content was similar to the opposite trace of the boron content. Therefore, the durability of suppression of the oxygen release is considered to be determined by the amount of consumed decaborane during the boronization session. This is supported by a comparison between 12th boronization using 70 g and 18th boronization using 20 g of $B_{10}D_{14}$. Before each boronization, similar amount of the maintenance work was done during vacuum vessel ventilation, and the reduction of the oxygen content by each boronization was similar (see Table 1, later). As shown in Fig. 4, the oxygen content recovered rapidly in the case of 18th boronization, and it reached 1.2% in ~30 shots. Comparison between the 12th (Fig. 2(c)) and the 18th boronization (Fig. 4) indicates that 20 g of decaborane might be insufficient to obtain long durability for the surface area of JT-60U (~200 m^2).

Table 1
Summary of boronization after vacuum vessel ventilation

Boronization	$B_{10}D_{14}$ (g)	Thickness (nm)	n_O/n_e (%)	Amount of work
12th	70	~135	1.5 → 0.7	Large
13th	20	~145	2.9 → 0.4	Limited
18th	20	–	1.7 → 0.8	Large
24th	20	–	1.3 → 0.7	Limited

The boronization session number, the amount of comsumed decaborane, measured thickness of the boron film, the core oxygen content in the L-mode period before and after the boronization and the amount of maintenance work during the ventilation are shown.

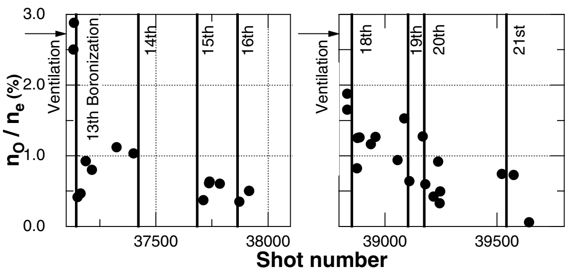

Fig. 4. The oxygen content in the L-mode period as a function of shot number.

Table 1 summarizes results of the boronization after vacuum vessel ventilation. Here, 'Large' and 'Limited' mean that the vacuum vessel was open over 1 month and open only in few days, respectively. Each boronization could reduce the oxygen content to 0.4–0.8% in spite of different conditions of boronization, i.e. the amount of comsumed decaborane, the oxygen content before boronization and the amount of maintenance work. Therefore, the reduction of the oxygen content does not seem to depend on conditions before boronization nor the amount of consumed decaborane while the durability depends on the amount of consumed decaborane.

Fig. 4 also shows the result of an attempt to keep the oxygen content low by continual boronization using 10–20 g of $B_{10}D_{14}$ every ~200 shots. The oxygen content less than ~1.0% was successfully sustained. The result indicates that 20 g of $B_{10}D_{14}$ is sufficient for continual boronization although the durability of boronization using 20 g of $B_{10}D_{14}$ is short.

Fig. 5 shows Z_{eff} as a function of the line-averaged electron density. In order to discuss boronization effects on impurities, the data taken in 50 shots after boronization is compared with the data in the other shots. As described above, the boron content is high while the carbon content is low due to suppression of the chemical sputtering of the carbon tiles, and the oxygen release is suppressed after boronization. Therefore, Z_{eff} in 50 shots after boronization lies in the lowest range of the database in the OH and the L-mode periods although Z_{eff} in the H-mode period scatters.

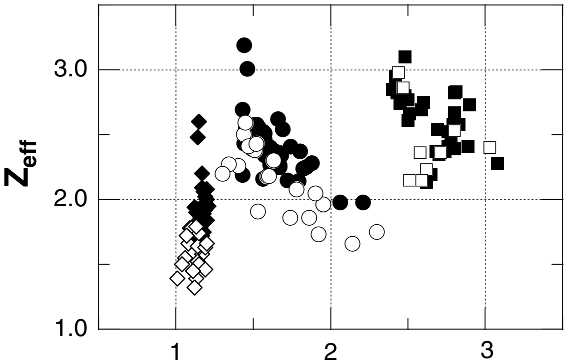

Fig. 5. Z_{eff} in the OH (diamond), L- (circle) and H-mode (square) as a function of the line-averaged electron density. Open and closed symbols show Z_{eff} in 50 shots after boronization and in the other shots, respectively.

4. Summary and conclusions

From the above results, boronization after vacuum vessel ventilation can reduce the oxygen content to ~0.6%. However, since the durability of the boronization effects using 20 g of $B_{10}D_{14}$ is much shorter than that using 70 g, more than 70 g of $B_{10}D_{14}$ should be consumed for the first boronization after vacuum vessel ventilation. Once the oxygen content decreases to ~1.0% by the boronization using 70 g of $B_{10}D_{14}$, the effects are considered to last for several hundreds of shots. Since then, 10–20 g of $B_{10}D_{14}$ for continual boronization every ~200 shots is considered to be sufficient to keep the oxygen content less than 1.0%. The boron film can suppress the chemical sputtering of carbon tiles. The durability of this effect is only ~50 shots in the case of boronization using 70 g of $B_{10}D_{14}$. If thicker boron film covers carbon divertor tiles around the strike points, the carbon content could be suppressed at a low level for longer duration. Due to suppression of the chemical sputtering of carbon tiles and of the oxygen release, Z_{eff} in 50 shots after boronization lies in the lowest range of the database, which includes ~100 discharges with identical conditions.

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