Journal of The Physical Society of Japan
Vol. 61, No. 9, September, 1992, pp. 3030–3033

First Results of Boronization in REPUTE-1 RFP

Shunjiro SHINOHARA, Ken-ichi YAMAGISHI, Satoshi OHDACHI,
Akira EJIRI,* Hiroshi TOYAMA and Kenro MIYAMOTO**

Department of Physics, Faculty of Science, University of Tokyo,
Bunkyo-ku, Tokyo 113

(Received May 13, 1992)

The first boronization in a reversed field pinch machine has been carried out and its effects on plasma performance have been studied. From a residual gas analysis, it was found that total and partial pressures were reduced. During the first several tens of discharges, the mean plasma density normalized by a filling pressure became much higher and was nearly constant during a discharge, but these phenomena became weaker shot by shot. Radiated power, plasma resistance, CrI line intensity and high-frequency magnetic oscillations decreased. The ion temperature from Doppler broadening of the CV line changed only slightly, whereas lower temperature from the OV line was found.

[plasma, RFP plasma, boronization, conditioning, radiation loss, residual gas analysis, ion temperature]

§1. Introduction

In a reversed field pinch plasma (RFP),[1] which has greater current density and wall power loading than a tokamak, wall-plasma interaction[2] is a critical issue to be investigated. Presently, radiated power is small compared with ohmic power (typically ~10% level), and it has not resulted in drastic deterioration of the plasma performance. This is because the electron temperature is less than 1 keV, edge temperature is low such that I/N does not become large[3] (I: plasma current, N: line density) and discharge duration time is short for the inner wall material to be heated to a certain temperature. However, the metal, as well as light impurities, will become important with increases in temperature and duration time, and play a significant role in determining the resistivity and radiated power.[3] Unless wall conditioning and plasma facing materials are carefully considered for future large RFP machines, good plasma performance will be impaired.

Therefore, studies on wall conditioning and limiter/wall materials are crucial. Covering graphite tiles[4] or testing limiter materials[5] showed the importance of reducing impurities. As for wall conditioning, only a few experiments such as glow discharge cleaning and carbonization have been performed in RFP machines.[6–8] In addition, a lower (than carbon; charge $Z=6$) Z coating on the wall surface in order to decrease the impurity radiated power has not been applied at all in a RFP device. On the contrary, boronization[9–11] ($Z=5$) and Be ($Z=4$) evaporation and tiles[12] have been employed to obtain better plasma parameters in tokamaks.

Here, we present the first results of wall conditioning by boronization to establish the effects on plasma performance, especially radiated power and impurity intensities, in the REPUTE-1 RFP machine.[13,14] The obtained data are useful and form a valuable database for further investigation of a larger RFP machine. First, glow discharge conditions and residual gas analysis are described in §2. Section 3 next deals with effects on plasma parameters comparing before and after boronization. Finally, conclusions are presented in §4.

§2. Conditions of Boronization and Residual Gas Analysis

Instead of diborane B_2H_6, the working gas for boronization was boron-trimethyl

---

* Present address: National Institute for Fusion Science, Chikusa-ku, Nagoya 464-01.

** Present address: Department of Applied Physics, Faculty of Engineering, Seikei University, Musashino-shi, Tokyo 180.

$B(CH_3)_3$, which is less toxic,[10,15] diluted by He gas (concentration of $B(CH_3)_3$ is 11%). Typical glow discharge conditions using a molybdenum anode head 23 mm in diameter, were P_T (total pressure) = 20-50 mTorr, V_A (anode voltage) = 200-350 V, and I_A (anode current) = 1.5-1.8 A, which corresponds to 21-25 $\mu A/cm^2$. This discharge (the working gas was fed without pumping for constant pressure and was replaced several times) was carried out for four hours. The flow mode (the gas was continuously fed with pumping) was applied for an additional 20 minutes. The mixed layers of carbon and boron produced were estimated to be several tens of nm thick.

After boronization, total and partial pressures of water and oxygen decreased from a residual gas analysis. On the contrary, partial pressures of hydrocarbons drastically increased: low mass (m) numbers (less than 20), intermediate m of 35-45 and 55 (same mass as $B(CH_3)_3$) and high m of 80 and 82 including 79 and 81. Hydrocarbons larger than $m=50$ were below the detected level before boronization, but all these signals faded after successive plasma discharges. Hydrogen pressure also decreased by ~40% after several tens of discharges. At this stage, decreases in total and partial pressures of water and oxygen were ≥30%, factors of ~4 and ~2, respectively.

§3. Plasma Performance after Boronization

Immediately after boronization, mean plasma density $\bar{n}_e$ was extremely high compared with a typical density (before boronization) of less than $10^{14}\,cm^{-3}$, and also higher than the expected density $\bar{n}_{ef}$, as shown in Fig. 1(a). Here, $\bar{n}_{ef}$ is the calculated density assuming complete ionization of the filling (hydrogen) gas. This $\bar{n}_e$ was nearly constant with time, i.e., no pump out, contrary to the case before boronization. These findings are mainly due to the fact that boronization was carried out in a vacuum vessel at room temperature and without He glow discharge after boronization, which meant that the coated layers contained abundant hydrogen. For the case of carbonization,[8] $\bar{n}_e$ was not as high compared with that of boronization, but the time behavior of $\bar{n}_e$ during a discharge was nearly the same (~constant density). After several tens of discharges, $\bar{n}_e$ could be controlled to a lower level, and slight pump out phenomena were evident in the next several tens of shots because of the release of hydrogen from the layers.

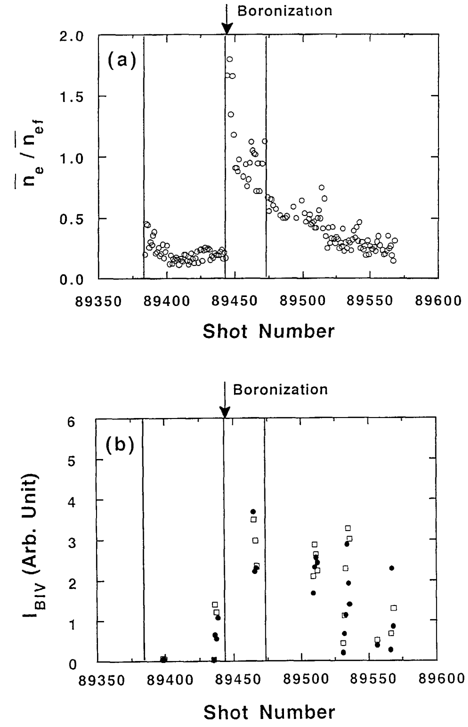

Fig. 1. Normalized mean plasma density $\bar{n}_e/\bar{n}_{ef}$ (a) and BIV line intensity (closed circles: intensity itself, open boxes: intensity normalized by $\bar{n}_e$) (b) as a function of shot number of discharges ($\bar{n}_{ef}$: expected plasma density from full ionization of the filling gas). Vertical lines determine three successive days and an arrow shows the time of boronization.

At a later stage of discharge duration, the decay of plasma current I_p was slower than before horonization, and accompanied by a large reduction of small increases in the loop voltage V_l and intensities of impurity lines. Note that V_l and impurity intensities were high near the end of discharge before boronization. As shown in Fig. 1(b), a gradual decrease in BIV line intensity (ionization potential $I.P.$ is 260 eV, wavelength λ is 282.5 nm) was observed shot by shot, although there was scatter due to the different conditions, such as I_p and $\bar{n}_e$, between shots. This trend as a function of shot was also observed in CV (I.P. = 392 eV, $\lambda = 227.1$ nm) line intensity.

Hereafter, we used the data taken in the latter half of the next day after boronization, since plasma parameters did not change very much shot by shot compared with those immediately after boronization.

Before boronization, F and Θ values for good plasma discharges were typically around -0.5 and 2.1, respectively. Here, F and Θ are ratios of the poloidal and toroidal fields at the wall to the mean toroidal field, respectively. After boronization, the value of F became shallow (~ -0.25) and a decrease in Θ (~ 1.8) was observed. Using a modified Bessel function model[16] with β (poloidal beta value) $=0.1$, α was changed from ~ 0.9 to ~ 0.7, which showed a broader μ (ratio of current density to magnetic field) profile after boronization. Here, α is the index of the μ profile expressed as μ being proportional to $(1-r^2)^\alpha$.

Figure 2 show the relationship between radiated power P_r and $\bar{n}_e$ due to the effect of boronization. Here, P_r was measured by a germanium thermistor bolometer (nearly central chord) for about $I_p=210$ kA. The value of 5 of P_r corresponds to 5 MW, if uniform radiation from the plasma can be assumed, which was about 12% of the total input power. From this figure, a reduction of P_r after boronization was found, particularly in the range of $\bar{n}_e=(3\text{–}5)\times 10^{13}\ \text{cm}^{-3}$. Decreases in plasma resistance R_p (I_p/V_l at the time of the peak plasma current) by $\sim 10\%$ and metal impurity intensity of the CrI line ($\lambda=427.5$ nm), which reflects the plasma-wall interaction, by more than a factor of two were also observed. This R_p became more weakly dependent on $\bar{n}_e$ after boronization, whereas a clear positive correlation between R_p and $\bar{n}_e$ was found before boronization.

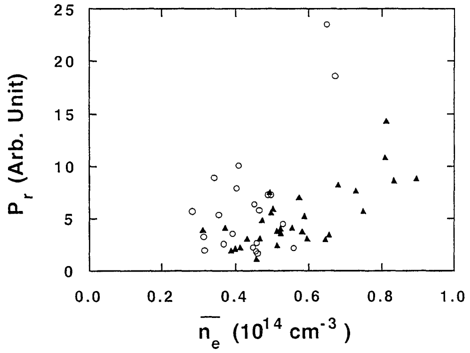

Fig. 2. Relationship between radiated power P_r and mean plasma density $\bar{n}_e$ for about $I_p=210$ kA before (open circles) and after (closed triangles) boronization.

As for the central electron temperature $T_e(0)$ measured by the Thomson scattering method, no appreciable change was found after boronization. Ion temperature T_i, due to Doppler broadening of the CV line as a function of the I/N value, did not change very much, as is shown in Fig. 3(a). This is completely different from the carbonization case,[8] in which CV temperature decreased with a decrease in the input power. This difference may be a result of thinner layers (several tens of nm for the boronized case and 55–140 nm for the carbonized case) and the different composition of layers; the ratio of boron to carbon in the mixed layers was ~ 0.4 for the boronization case.[12] (By means of the charge exchange neutral particle analyzer, no drastic change of T_i was found.) On the contrary, T_i from the OV line (I.P. $=114$ eV, $\lambda=278.1$ nm) decreased, as in Fig. 3(b). This may be due to the change of the electron temperature profile after boronization, as indicated from the results that T_e at $a/4$ (a: plasma radius) normalized by $T_e(0)$ increased, which is consistent with the broader μ profile obtained from F and Θ values described above. This is because the OV line intensity is considered to be maximum not at the plasma center, but at the intermediate position of the plasma radius. The OV temperature decrease may also be partly due to the change of the ion temperature profile. In addition, amplitudes of high-frequency (50–250 kHz) magnetic field fluctuations lower by a few tens of % were obtained, which were measured by magnetic probes located on the inner surface of the vacuum chamber.[17] This is consistent with the results that the OV temperature decreases with the decrease in the high-frequency components of magnetic fluctuations for the unboronized case.* The decrease in the fluctuations may be related to the non-Spitzer part of resistivity, which is considered to contribute to ion heating. From the measurement of H_α ($\lambda=656.3$ nm) line intensity, no appreciable change was found. The soft X-ray intensities $I_{sx}(0)$ (central chord) and

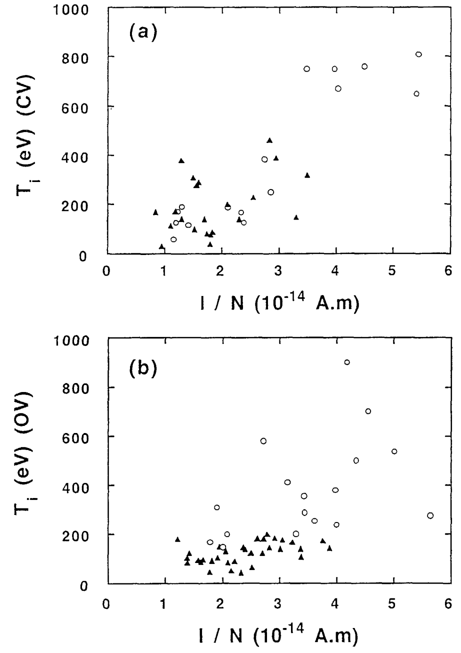

Fig. 3. Ion temperatures from Doppler broadening of CV (a) and OV (b) lines vs. I/N value before (open circles) and after (closed triangles) boronization. Here, I and N represent plasma current and line density, respectively.

$I_{sx}(a/4)$ (chord radius is $a/4$), and the ratio of $I_{sx}(a/4)/I_{sx}(0)$ decreased somewhat. Here, the soft X-ray intensity contains the impurity component as well as the electron temperature and density. From the T_e and $\bar{n}_e$ measurements, a decrease in this intensity reflects a reduction of impurity radiation, which is consistent with the decrease in the radiated power, as shown in Fig. 2. A decrease in $I_{sx}(a/4)/I_{sx}(0)$ indicates relative reduction of the radiation on the outside of the plasma core. Contrary to the expectation that boronization reduces oxygen impurity,[2)] the OV line intensity did not decrease appreciably, although the partial oxygen pressure decreased from a residual gas analysis. Note that the OV line intensity did not directly reflect the plasma surface interaction, since the emitted region is an intermediate plasma radius.

These favorable effects by boronization described so far, such as decreases of P_r, R_p, CrI intensity and magnetic fluctuations, gradually faded after a few hundreds of plasma discharge shots.

§4. Conclusions

For the first time, boronization in a reversed field pinch machine has been performed for the purpose of wall conditioning, and its effects on plasma performance have been investigated. From a residual gas analysis, total and partial pressures of hydrogen (after plasma discharges), oxygen and water were reduced. During the first several tens of discharges, mean plasma density $\bar{n}_e$ became much higher with nearly constant density during a discharge, i.e., there was no pump out, and $\bar{n}_e$ normalized by the filling pressure $\bar{n}_{ef}$ decreased shot by shot.

The values of Θ became lower and F, shallower, which indicate a broader μ profile. It was found that P_r, R_p, CrI line intensity and high-frequency (50–250 kHz) magnetic oscillations decreased. The CV temperature changed only slightly, whereas a lower OV temperature, whose maximum intensity does not originate from near the plasma center, was obtained.

References

1) H. A. B. Bodin: Nucl. Fusion **30** (1990) 1717.
2) P. C. Stangeby and G. M. McCracken: Nucl. Fusion **30** (1990) 1225.
3) P. G. Weber: Phys. Fluids **28** (1985) 3136.
4) T. Tamano *et al.*: Plasma Physics and Controlled Nuclear Fusion Research, 1985 (*Proc. 10th Int. Conf. London, 1984*) Vol. 2, p. 431.
5) Y. Hirano *et al.*: Plasma Physics and Controlled Nuclear Fusion Research, 1991 (*Proc. 12th Int. Conf. London, 1990*) Vol. 2, p. 717.
6) K. F. Schoenberg *et al.*: Plasma Physics and Controlled Nuclear Fusion Research, 1987 (*Proc. 11th Int. Conf. Kyoto, 1986*) Vol. 2, p. 423.
7) G. L. Jackson *et al.*: J. Nucl. Mater. **145–147** (1987) 470.
8) S. Shinohara *et al.*: Plasma Phys. & Controlled Fusion **34** (1992) 627.
9) J. Winter *et al.*: J. Nucl. Mater. **162–164** (1989) 713.
10) S. J. Fielding *et al.*: *Proc 18th European Conf. on Controlled Fusion and Plasma Heating, Berlin, 1991*, Vol. 15C Part III, p. 73.
11) G. L. Jackson *et al.*: Phys. Rev. Lett. **67** (1992) 3098.
12) JET Team: Plasma Physics and Controlled Nuclear Fusion Research, 1991 (*Proc. 13th Int. Conf Washington, 1990*) Vol. 1, p. 27.
13) S. Shinohara *et al.*: *Proc. 17th European Conf. on Controlled Fusion and Plasma Heating, Amsterdam, 1990*, Vol. 14B Part II, p. 541.
14) K. Miyamoto *et al.*: Plasma Physics and Controlled Nuclear Fusion Research, 1991 (*Proc. 13th Int. Conf. Washington, 1990*) Vol. 2, p. 525.
15) J. Winter *et al.*: J. Nucl. Mater. **176–177** (1990) 486.
16) A. Fujisawa, S. Onodera and K. Miyamoto: J. Phys. Soc. Jpn. **58** (1989) 473.
17) H. Ji *et al.*: Rev. Sci. Instrum. **62** (1991) 2326.

---

* A. Ejiri: private communication.