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A. Sagara, Y. Hasegawa, K. Tsuzuki, N. Inoue, H. Suzuki, T. Morisaki, N. Noda, O. Motojima, S. Okamura, K. Matsuoka, R. Akiyama, K. Ida, H. Idei, K. Iwasaki, S. Kubo, T. Minami, S. Morita, K. Narihara, T. Ozaki, K. Sato, C. Takahashi, K. Tanaka, K. Toi and I. Yamada

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Real Time Boronization Experiments in CHS and Scaling for LHD

A.Sagara, Y.Hasegawa[1], K.Tsuzuki[2], N.Inoue,
H.Suzuki, T.Morisaki, N.Noda, O.Motojima, S.Okamura, K.Matsuoka,
R.Akiyama, K.Ida, H.Idei, K.Iwasaki[2], S.Kubo, T.Minami, S.Morita, K.Narihara,
T.Ozaki, K.Sato, C.Takahashi, K.Tanaka, K.Toi and I.Yamada

National Institute for Fusion Science, Nagoya 464-01, Japan
[1] *Nagoya Univ., Dept. of Energy Engrg. and Science, Nagoya 464-01, Japan*
[2] *The Graduate University for Advanced Studies, Nagoya 464-01, Japan*

abstract

As a promising wall-conditioning technique in LHD under steady-state high magnetic fields with superconducting magnets, Real Time Boronization (RTB) by puffing decaborane $B_{10}H_{14}$ into the main NBI-heated plasma has been first examined in CHS. It is shown that, as compared with the usual glow discharge method, only the 2 orders smaller amount of decaborane is efficient to reduce plasma impurities such as oxygen and metals, resulting in expansion of the operating region of the plasma density and stored energy. The puffing at the inside of the LCFS gives better results on RTB than the outer. Even after RTB on the wall at the room temperature, hydrogen recycling does not increase probably due to the small consumed amount with a high plasma heating power used. The operative RTB parameters expected in LHD are estimated using the first scaling of boronization on the device size.

Key words: LHD, wall conditioning, wall coating, boronization, gas puffing.

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1. Introduction

In the LHD project [1], since the superconducting (SC) magnet current is continuously driven for twelve hours, a wall conditioning technique to apply low-Z coatings, under a high magnetic field, is desired. For this purpose, Real Time Boronization (RTB) method is quite promising.

So far the RTB method has been developed by using a boron-containing graphite [2,3] or by puffing trimethylboron $B(CH_3)_3$ gas [4,5,6], giving potential results as a complementary way to prevent deterioration of pre-conditioned wall performance, in particular, in long discharge experiments. Since RTB actively utilizes a high magnetic field and high heating power for the main plasma, higher fueling efficiency and film quality in boronization are expected in comparison with conventional methods such as glow discharges. This novel feature of RTB should be noted as a suitable method in SC systems. However, controllability and effectiveness of RTB have not been clearly demonstrated and characterized yet.

In the present work, RTB by puffing decaborane $B_{10}H_{14}$, which is a less hazardous carbon-free boride with a low H/B atomic ratio [7], is first examined in NBI-heated plasma in CHS. Gas puffing RTB can be operated by changing puffing rate, timing, and nozzle position. Effects on impurity reduction and hydrogen recycling are evaluated. They depend on the puffing amount and puffing position.

Finally the operative RTB parameters expected in LHD are estimated. For this purpose a scaling of boronization parameters on the device size is first proposed by utilizing the data base thus far obtained with decaborane in a wide variety of experiments including laboratory devices and large plasma machines [8,9,10,11,12].

2. Experiments in CHS

Figure 1 shows the decaborane gas puffing device on the movable Limiter Experiments Test-stand (LET) placed at the down side of the torus of the 8-field-period heliotron/torsatron-type Compact Helical System (CHS) [13]. In this work the CHS was operated at a fixed condition of the magnetic field strength B_t=1.2Tesla with the plasma major radius R_{ax}=0.921m, where the last closed magnetic flux surface (LCFS) touches the inner side wall of the stainless steel chamber as a kind of limiter.

The gas puffing device consists of a decaborane oven, a pneumatic valve, a reservoir with a diaphragm pressure gauge, a heatable piezo valve, and an injection nozzle with a graphite cover. This device was all operated at 120°C, at which the vapor pressure of decaborane was as high as 40 mTorr [7]. The injected gas amount per shot was measured from the pressure change at the reservoir, whose volume of 65 cm^3 was optimized to keep the pressure change as low as 5% during an injection.

By changing the decaborane puffing position, two cases of experiments were performed, namely injections from 20mm inside (7% of the plasma minor radius a_p) and 125mm outside (45% of a_p) from LCFS, while the main H_2 gas-puffing position was fixed at the chamber wall. Figure 2 corresponds to the 20mm inside case, showing the time trace of $B_{10}H_{14}$ puffing of typical 5 Torr l/s for 50 ms with H_2 puffing, the port-through NBI heating power P_{in}, the plasma stored energy, the line-averaged density $<n_e>$, the total radiation loss power P_{rad}, and the VUV radiation of OV measured at the 180° toroidal position from the LET. An increase of the stored energy is observed after terminating gas puffing. This behavior, so called "reheat" [14], is beyond the scope of this paper.

3. Results and discussion

3.1 Reduction of plasma impurities

Figure 3 clearly shows that, under RTB with inside injection, the OV intensity decreased shot by shot, and, in about 10 shots, reached to a low level obtained after RTB. Here the wall condition "before RTB" means the condition before titanium flashing, which is always needed a few times each day to overcome radiation collapse at a high plasma, as seen actually in Fig.3 [10]. It is observed that the RTB suppressed the oxygen impurity, resulting in expansion of the operating region of the plasma density as well as an increase in stored energy up towards values expected in the LHD scaling [15]. Suppression of other impurities of C, Ti and Fe was also spectroscopically observed in visible or VUV light.

It should be noted that the data points in Fig.3 were taken at the peak of line averaged density in each shot, namely at the quasi-steady state, by changing the H_2 gas puffing rate shot by shot. Therefore, judging from the data number, the lifetime of good conditions after RTB is longer than 10 shots, in other words, comparable with the total RTB time.

The most important result in this work is that the total puffing amount of decaborane was only 53 mg in 30 shots, which is equivalent to the averaged film thickness of 2nm. This amount is almost 2 orders smaller than that used in the conventional method such as glow discharge [10], giving advantages in reducing a concern about flake dusts of coated films and hydrogen recycling. This result agrees with that obtained in TEXTOR [4], and can be explained by assuming the coating of "preferential" or "wetted" small areas of the chamber[6]. In fact the inner-side wall area interacting with LCFS as seen in Fig.1 is calculated to be about 0.5 % of the chamber wall in the experimental condition of this work.

3.2. Dependence on the puffing position

Two cases of decaborane injection were examined: one was puffing from 20mm inside from LCFS, the result of which was already shown in Fig.3; the other was from 125mm outside. In both cases the "before RTB" conditions were comparable as shown in Fig.4, and the total amount of consumed decaborane was equal to 53mg. Figure 4 clearly reveals that the radiation loss power was more efficiently suppressed due to the inside injection than the outside one.

It is conjectured from the present result that boride gases injected into LCFS might be highly decomposed and ionized due to the high heating power, and then, distribute far into the torus along the high magnetic field by avoiding local deposition near the puffing nozzle. In fact it is observed in Fig.5 that the VUV intensity of BII is stronger in case of the inside injection than the outside one under the equal puffing rate of RTB. In case of the outside injection, according to a thermal neutral Li beam probe [16] located in close vicinity of the RTB nozzle, the electron density at the outside region of LCFS significantly increased, suggesting an enhanced decomposition of decaborane in the scrape-off layer near the nozzle.

From engineering aspects, though the inside injection is efficient as far as RTB is concerned, just outside of LCFS is recommended as the optimum position to avoid the high heat flux on the puffing nozzle.

3.3 Effects on hydrogen recycling

In conventionally boronized walls using boride gases in such as glow discharge, it is usually needed to lower the hydrogen content in boron films by heating at more than 200°C or by bombarding with He discharges [7, 10]. However, the baking procedure to reduce hydrogen recycling is not always possible in any machines. In fact the wall temperature in LHD is limited below 100°C from the viewpoint of heat load onto superconducting magnets.

In Fig.3 it should be noted that the low density discharge, $\langle n_e \rangle \sim 1 \times 10^{13}$ cm^{-3} sustained with only wall fueling without H_2 puffing, was still reproducible even after RTB at room temperature, suggesting the hydrogen recycling to be comparable as before RTB. Moreover, even under the same rate puffing of H_2 gas, Fig.6 shows the Hα intensity to be smaller after RTB than before, indicating reduction of hydrogen recycling.

To understand the present result, it is helpful to note the two advantages in RTB: one is the 2 orders smaller amount of introduced decaborane than conventional methods as remarked in the section 3.1. The other is that RTB can use the high heating power of main plasma discharges. In fact, in our laboratory experiments, the hydrogen content in boron films decreased even at room temperature with increasing the input power for boronization

[8]. The reason is not clear yet. One of speculations is that, due to enhanced dissociation of boride molecules, H_2 gas products might be efficiently evacuated.

3.4 Scaling for LHD

To obtain the same performance of RTB in LHD as obtained in CHS, the boronization parameters required for the input power P_{in} [W], the total time T_b [s] of coating, and the total mass W_b [g] of boride required were estimated. For this purpose a scaling of boronization parameters as a function of the geometrical total area A_t [m^2] of the plasma-facing chamber wall has been first proposed by utilizing the data base so far obtained in conventional boronization with decaborane.

Table 1 summarizes boronization parameters reported in a wide variety of experiments including laboratory devices [8,9] and plasma machines [10,11,12] including the present RTB. When the total input power is supposed to be distributed to the decaborane gas in only proportion to its volumetric mixing ratio ξ in the total gas throughput with He, the distributed energy E_d [J/g] to boride gases is simply expressed as follows,

$$E_d = \xi P_{in} T_b / W_b \quad , \qquad (1)$$

$$W_b = k_b \eta A_t \quad , \qquad (2)$$

where η is the ratio of effectively coated area to A_t, and the total mass W_b is expected to simply proportional to the area ηA_t with a constant k_b to form an effective thickness of coating, which is at least about 100nm in conventional coating [9] and really observed around 100nm within factor 5 as listed in Table 1. In this scaling, a homogeneous coating is supposed in the area ηA_t .

Figure 7 shows that the values in Table 1 are well explained using eqs.1 and 2, revealing that, in case of conventional coatings, E_d is almost constant at 150 kJ/g (=190 eV per $B_{10}H_{14}$) and $(\eta\ k_b)_{conv} \sim 0.4$ g/m^2 (=2x10^{17} $B_{10}H_{14}$ /cm^2). By supposing eqs.1 and 2 stand even in case of RTB, E_d(RTB) ~ 15 MJ/g and $(\eta\ k_b)_{RTB} \sim 0.004$ g/m^2. If this coefficient $(\eta\ k_b)_{RTB}$ could be used in LHD, the RTB in LHD requires about 1.2g of decaborane and the total puffing time of 6 sec under the steady state operation with the 3MW heating [1].

4. Conclusion

Real Time Boronization(RTB) by puffing decaborane $B_{10}H_{14}$ into the main NBI-heated plasma was first examined in CHS, giving remarkable results:

(1) 2 orders smaller amount of decaborane than conventional boronization methods was efficient to reduce plasma impurities such as oxygen and metals, resulting in expansion of the operating region of the plasma density and the stored energy.

(2) Since the inside injection from LCFS was efficient, the just outside of LCFS was recommended as the optimum position to avoid the high heat flux on the puffing nozzle.

(3) Even with the wall at room temperature, hydrogen recycling did not increase. This is probably due to the small amount of introduced decaborane and the high heating power of the main plasma during the B-deposition.

(4) The scaling of boronization parameters as a function of the total wall area was first proposed to control the performance of RTB in LHD.

In conclusion, from viewpoints of effectiveness, reproducibility and controllability, the gas-puffing RTB is quite promising as a wall-conditioning method in LHD under steady-state high magnetic fields in the superconducting magnet system.

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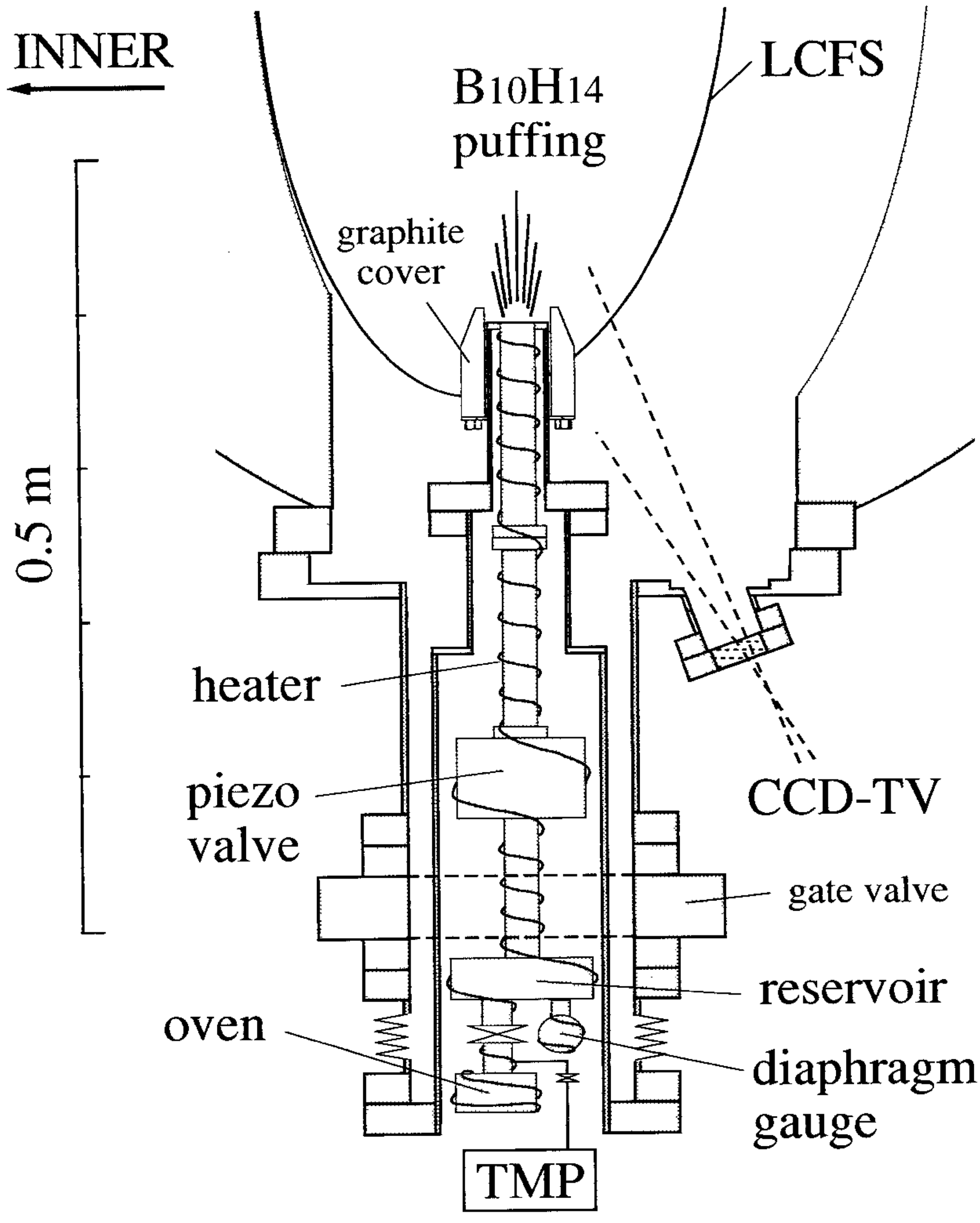

Fig.1 The movable gas-puffing RTB device in CHS.

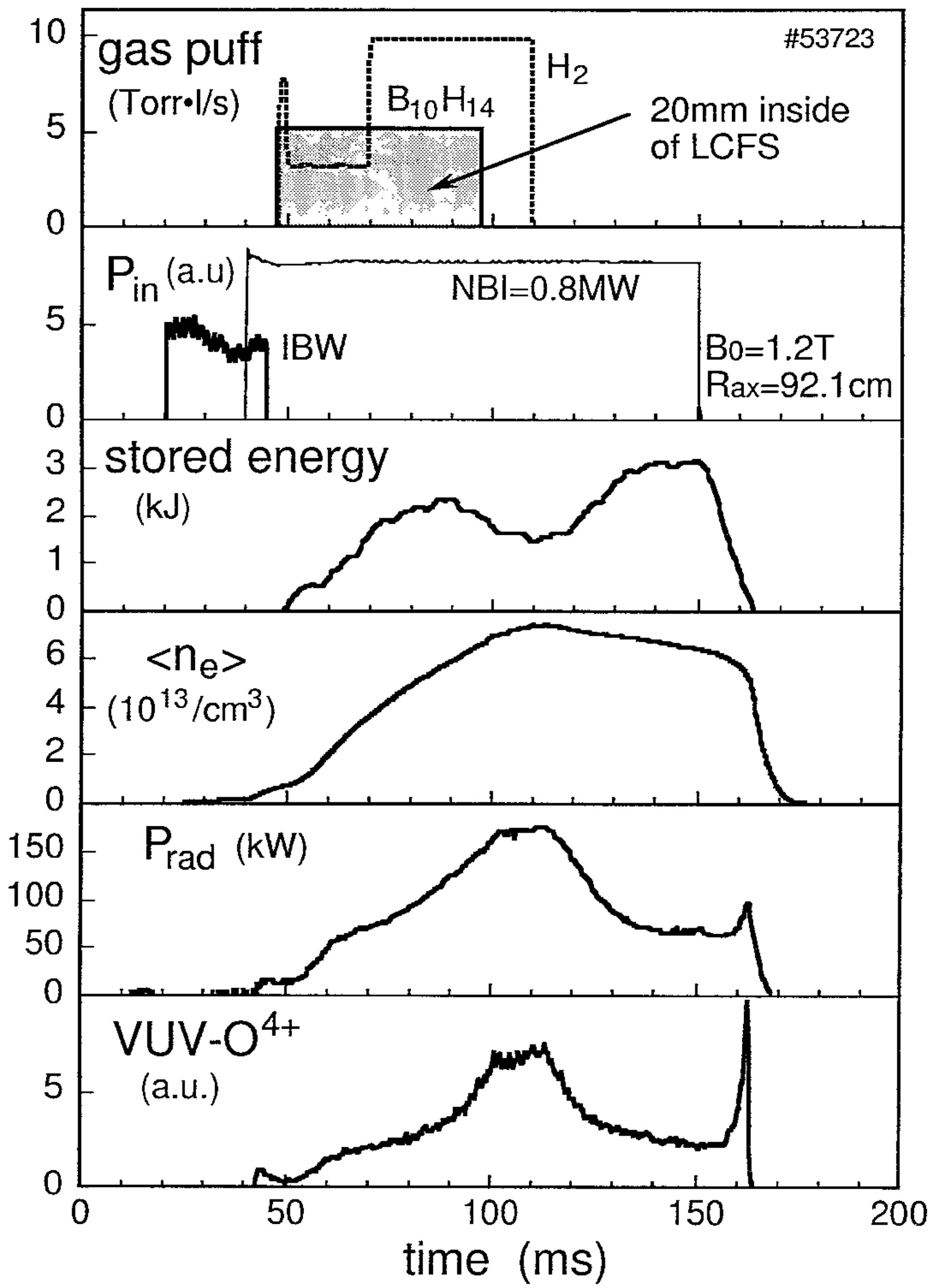

Fig.2 Typical time traces of the plasma under RTB.

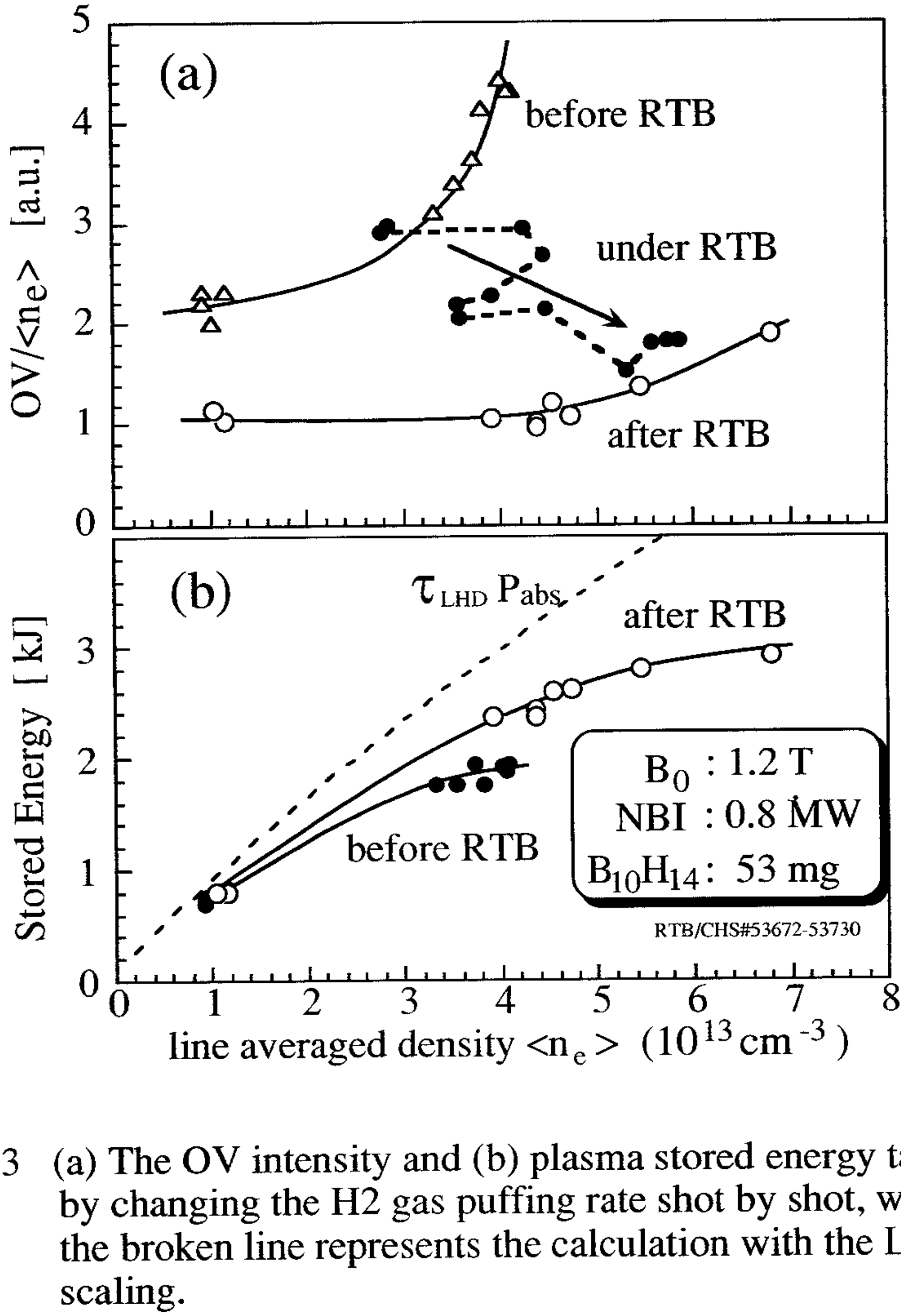

Fig.3 (a) The OV intensity and (b) plasma stored energy taken by changing the H2 gas puffing rate shot by shot, where the broken line represents the calculation with the LHD scaling.

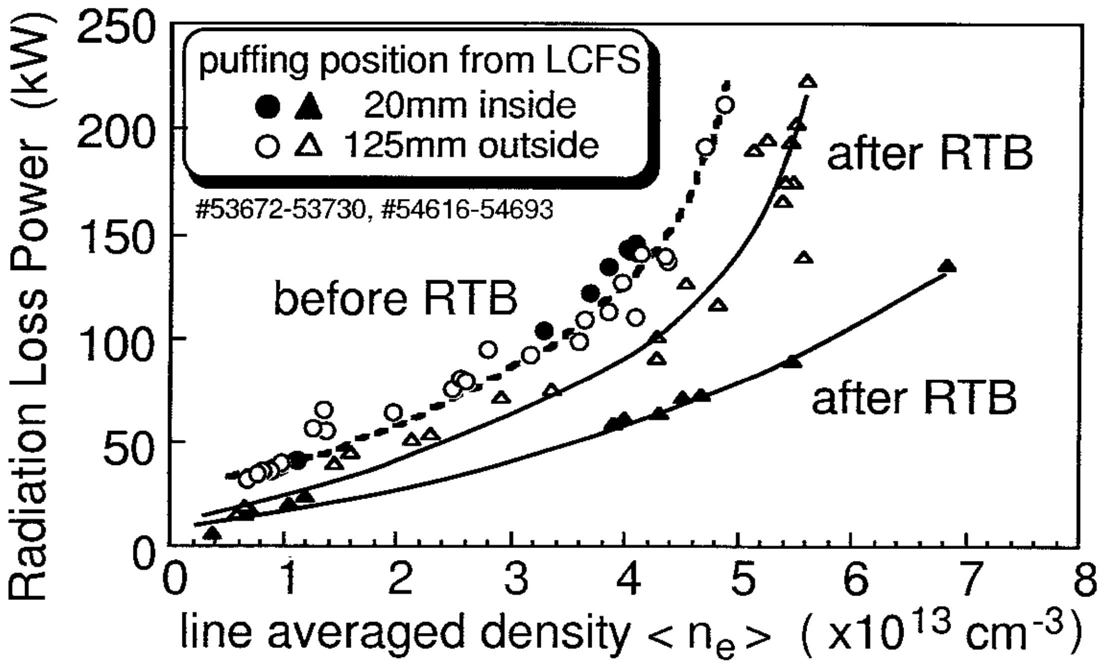

Fig.4 Comparison of RTB effectiveness between injections from the 20 mm inside and 125 mm outside from LCFS, where the total mass of decaborane used was 53 mg in both cases.

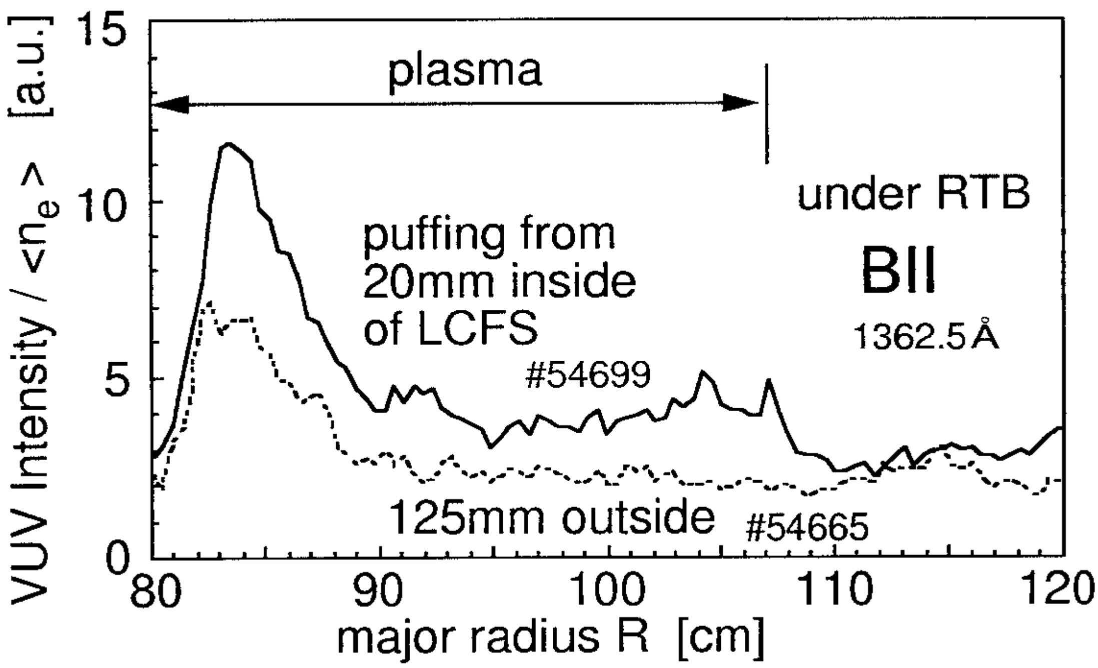

Fig.5 Comparison of BII poroidal distributions measured at the 180° toroidal position from the RTB nozzle under decaborane injections from the 125 mm outside (#54665) and 20 mm inside(#54699) from LCFS.

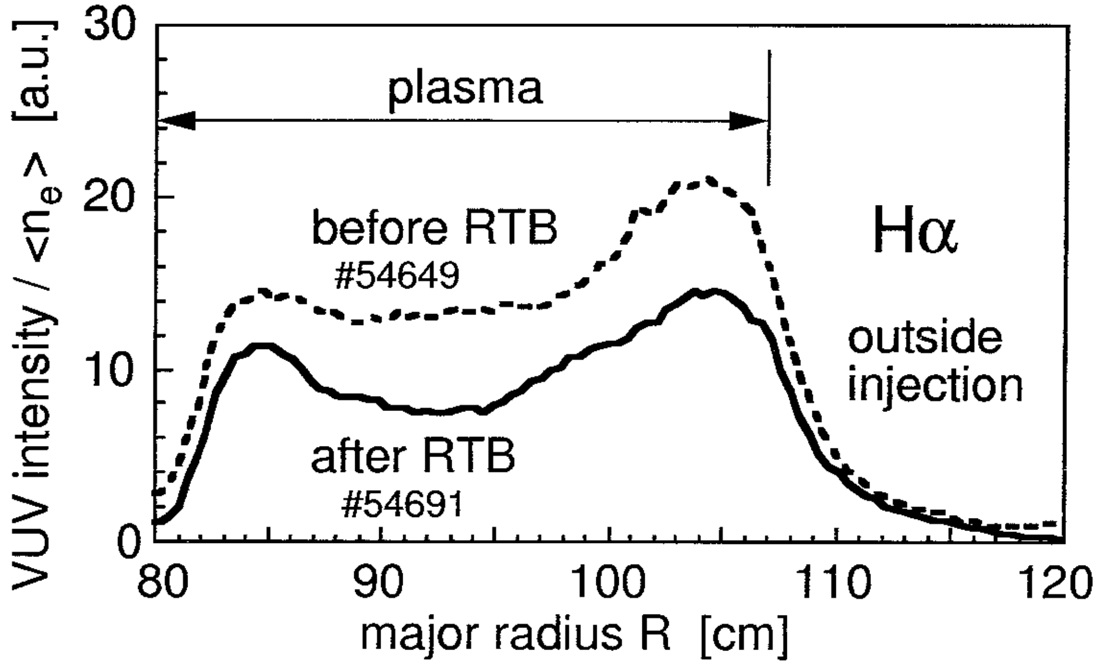

Fig.6 The poroidal distributions of the Hα intensity before and after RTB of the 125mm outside injection.

Table 1 Boronization parameters reported in many devices using decaborane with glow discharge(GD), electron cyclotron resonance(ECR) and the present RTB.

device	method	area (m^2)	mixing ratio	power (W)	total time	mass (g)	thick (nm)	E (kJ/g)	ref.
PPT	GD	0.11	0.06	340	5 min	0.016	30	369	8
PPT	GD	0.11	0.15	100	5 min	0.042	20	108	8
SUT	GD	0.70	0.04	150	30 min	0.063	135	171	9
CHS	RTB	12	1	7×10^5	1 s	0.05	2	14000	this work
CHS	GD	12	0.02	400	44 h	12	400	106	10
Hliotron-E	ECR	30	0.07	2000	11 h	10	200	554	11
JT-60U	GD	168	0.015	4800	60 h	100	250	144	12

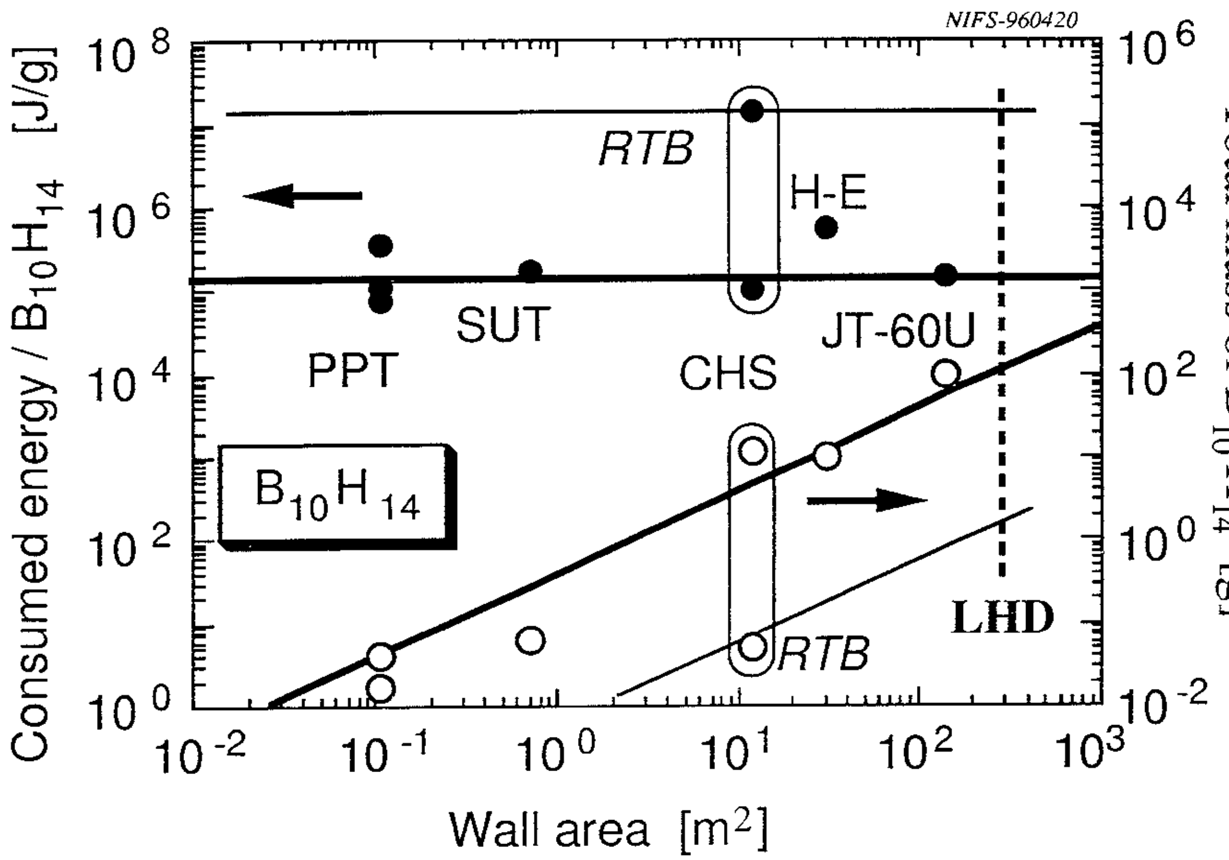

Fig.7 Boronization parameters reported in many devices using decaborane with conventional methods and the present RTB [8,9,10,11,12], where the lines represent eqs.1 and 2.

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