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Characteristics of carbon sheet pump in application experiments to a high-temperature plasma device

Y. Nakashima [a,*], A. Sagara [b], T. Moriwaki [a], Y. Hironaga [a], S. Kobayashi [a], Y. Ishimoto [a], M. Yoshikawa [a], T. Tamano [a], K. Yatsu [a], K. Tsuchiya [c], M Shoji [b], H. Suzuki [b], N. Noda [b], A. Komori [b], N. Ohyabu [b], O. Motojima [b]

[a] *Plasma Research Center, University of Tsukuba, Tennodai, Tsukba, Ibarki 305-8577, Japan*
[b] *National Institute for Fusion Science, Toki 509-5292, Japan*
[c] *Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka-machi, Ibaraki 311-0102, Japan*

Abstract

Carbon sheet pump (CSP), which has been developed for reduction of hydrogen recycling in the large helical device (LHD) of National Institute for Fusion Science, is applied to an actual plasma device for the first time to evaluate the pumping characteristics. A small scale of pump module is manufactured and installed in the GAMMA-10 tandem mirror device and the module is exposed to charge-exchange neutrals emitted from ICRF-heated hot-ion plasmas. Temporal evolution of the pressure is measured with a fast ionization gauge installed in the test chamber during the plasma discharge and a significant difference between CSP-on and CSP-off is observed under good reproducibility. The dependence on the ICRF power is investigated and the pressure difference between on and off is found to increase with the ICRF power. These phenomena indicating the pumping ability of CSP are observed to continue during more than 300 plasma shots, which shows the effectiveness of CSP in controlling hydrogen recycling. The result of thermal desorption experiments of CSP after being exposed to charge-exchange neutrals is also described.

Keywords: GAMMA-10; Tandem mirror; Carbon sheet pumping; Hydrogen pumping

1. Introduction

It has been pointed out from early studies that hydrogen recycling and its control are essential issues to improve the plasma performance of magnetic confinement fusion devices [1–4]. In various devices many kinds of wall conditioning methods have been developed to control hydrogen recycling, such as discharge cleaning techniques and wall-coating processes with low-Z materials. Recently a feasibility for hydrogen pump by using carbon material (carbon sheet pump [CSP]) has been proposed and designed for reduction of hydrogen recycling in the LHD device of National Institute for Fusion Science [5,6]. In Ref. [5] it is reported that a demonstration of hydrogen pumping by CSP was successfully carried out in a glow discharge. Carbon materials have been widely used as a first wall and a low-Z coating material in a large number of tokamak devices. The carbon sheet, which is made of C/C composite, has a large capacity to trap hydrogen atoms with high energy in the unsaturated region at a temperature below 200°C. CSP is therefore suitable for pumping charge-exchange neutral particles under low heat-loading conditions and can be easily regenerated by direct Joule heating owing to its thin-plate structure and relatively high electric resistivity. In this study, a small scale of pump module is designed and applied for the first time for pumping the charge-exchange neutrals emitted from ion cyclotron range of frequency (ICRF) heated plasmas produced in the GAMMA-10 tandem mirror device in

* Corresponding author. Tel.: 81 298 53 7473; fax: 81 293 53 6202; e-mail: nakashma@prc.tsukuba.ac.jp

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order to evaluate the pumping characteristics of CSP in cases actually applied to plasma devices.

GAMMA-10 is a tandem mirror device which consists of an axisymmetric central-mirror cell, anchor-cells with minimum-B field, and plug/barrier cells with axisymmetric mirrors [7]. The length of the central-cell is 6 m and the diameter of the vacuum chamber is 1 m. The magnetic strength in the central-cell mid plane is normally 0.43 T. In the central region strong ion heating is carried out by using ICRF waves and the plasmas relatively high ion temperatures (more than ~5 keV) have been achieved, which enable us to easily evaluate the pumping effect on high-energy neutrals [7–9].

2. Experimental apparatus

Fig. 1 shows the schematic view of the test chamber of CSP and the experimental set-up. The shape of the CSP is a disk with 170 mm diameter and 1.5 mm thickness. The material is a C/C sheet (Toyo Tanso, CX-260). The CSP is installed in a water-cooled vacuum chamber with a radiation shield for baking. The baking is carried out up to 800°C for outgassing the absorbed hydrogen by Joule heating of the carbon sheet. The test chamber has been mounted on the central cell vacuum chamber of GAMMA-10 with an inner diameter of 1 m. The CSP is located at the top of the vacuum chamber and is about 1.5 m away from the plasma center. Charge-exchange neutrals emitted from the plasma are introduced into the test chamber via an extension tube of 400 mm length. In front of the CSP, a stain-less steel shutter is placed and the pumping effect is examined by opening and closing the shutter shot by shot. In the present experiment the temporal evolution of pressures is measured with a fast ionization gauge installed in the test chamber and the results are compared between the cases with the shutter opened (CSP-on) and closed (CSP-off).

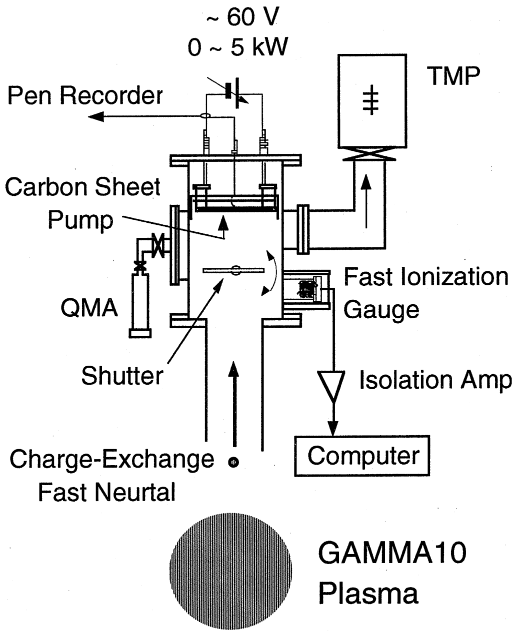


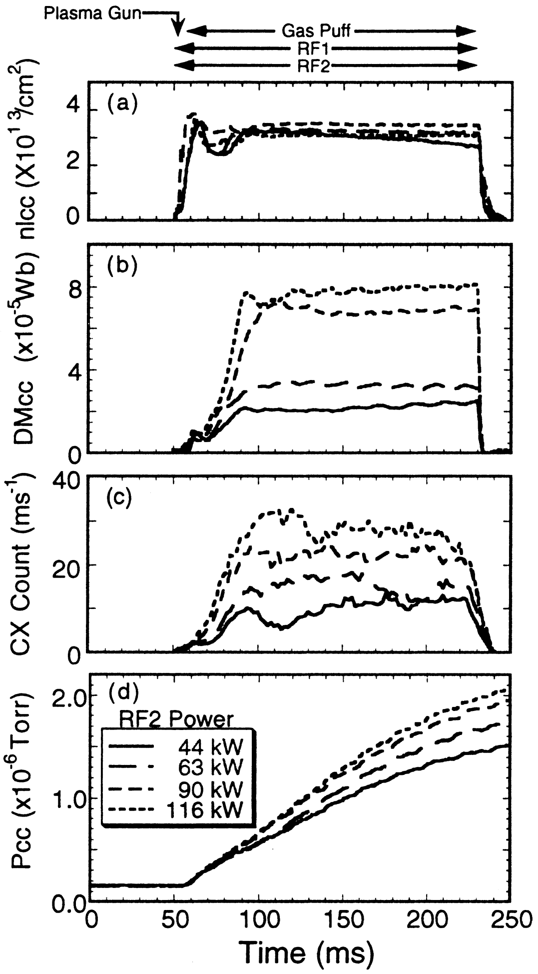
Fig. 1. The schematic view of the test chamber of CSP and the diagnostic system.

In standard ICRF-heated GAMMA-10 plasmas [7,10], the density of $\sim 3 \times 10^{12}$ cm^{-3}, the ion temperature of ~5 keV and the atomic hydrogen density of $\sim 5 \times 10^{8}$ cm^{-3} are achieved and the resultant flux intensity of charge-exchange neutrals on the interior wall surface is estimated to be about 5×10^{14} H atoms/cm^{2}s. The saturation level of implanted D at 1.5 keV has been measured to be $1–4 \times 10^{17}$ atoms/cm^2 [5,11], which provides the pumping duration time of 200–800 s in the GAMMA-10 plasma discharges. This value makes it possible to carry out the plasma experiments without regeneration of CSP for more than two months.

3. Application experiment to GAMMA-10 plasmas

A typical time behavior of the plasma parameters produced in the central cell of GAMMA-10 is shown in Fig. 2. Two kinds of ICRF waves (RF1 and RF2) are utilized for plasma production and heating in the central cell. In this experiment the ICRF power for ion heating (RF2) is varied from 44 to 116 kW. The electron line-density of 3×10^{13} cm^{-2} is sustained for about 150 ms in a steady-state phase corresponding to the ICRF pulse despite changing the ICRF power in every plasma shot. As shown in Fig. 2(b) and (c), the diamagnetism and charge-exchange neutral flux with the energy of 5.3 keV measured near the central mid-plane increase with the ICRF power. Fig. 2(d) shows the time variation of the pressure in the central cell vacuum chamber measured with a fast ionization gauge. Although the quantity of gas puffing is kept constant, it is found that the rising rate of the measured pressure increases with the ICRF power.

The energy distribution of charge-exchange neutrals is measured with a neutral particle analyzer located at the same position of the CSP test chamber. The energy spectra of hot ions obtained at a steady-state period ($t = \sim 150$ ms) are shown in Fig. 3. A remarkable increase of neutral flux in the high-energy range is observed and the ion temperature near the central core region is estimated to increase from about 2.5–5 keV according to the increase of the ICRF power on the basis of the charge-exchange neutral analysis and diamagnetic measurement. From the above results it is clear that the increase of the ion temperature along with the rise of the ICRF power causes an enhancement of high-energy charge-exchange neutrals.



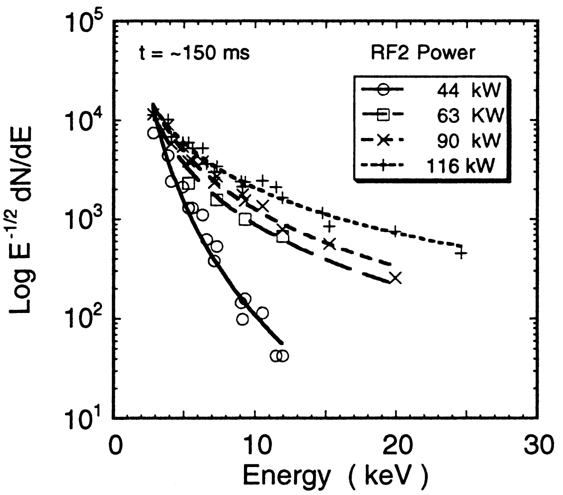


Fig. 3. Energy spectra of charge-exchange neutrals measured at the same location of the CSP test chamber.

Fig. 4(a) shows the temporal change of the pressure measured with a fast ionization gauge installed in the CSP test chamber during the plasma discharge. Bold lines represent the pressure in the case with CSP-off and narrow ones correspond to the case with CSP-on. In this experiment, rather large amount of gas is flowing into the test chamber during the plasma shot. The resultant change in cases with CSP-on and CSP-off appears to be small due to this gas influx. There is, however, a significant difference between CSP-on and CSP-off observed in the rising rate of every measured pressure under good reproducibility. This observation indicates that CSP traps the high-energy charge-exchange neutrals and reduces the pressure rise during the plasma discharge.

In Fig. 4(b), the pressure-difference between CSP-on and CSP-off is plotted as a function of time to investigate the above observation results in detail. It is found that in cases with higher ICRF power, the larger difference is observed during the plasma discharges and that the difference in every case begins to decrease just after the termination of the plasma discharge. This implies that the ion temperature rise due to the increase of ICRF power enhances hydrogen recycling in the central cell and leads to the enlargement of the pressure-difference since the ratio of charge-exchange flux to thermal gas influx in the test chamber increases. Furthermore, the

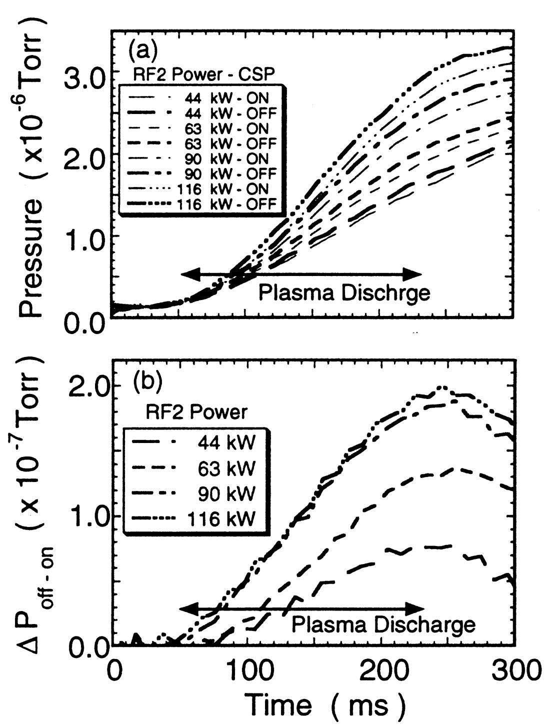


Fig. 4. (a) The time evolution of pressure in the test chamber measured with a fast ionization gauge. (b) The pressure-difference between CSP-on and CSP-off as a function of time.

time constant of the pressure decrease after the plasma is terminated is fairly comparable to the time constant of evacuation based on the conductance of the extension tube and the volume of the CSP chamber (~50 ms).

In order to investigate the relationship between the pumping effect and charge-exchange neutral flux, we made a rough calculation of pumping quantity from the pressure difference between CSP-on and CSP-off during the plasma discharges. Fig. 5 shows the correlation between the pressure difference multiplied by the volume of the CSP test chamber $\Delta P_{\mathrm{CSPoff-on}} \cdot V_{\mathrm{CSP}}$ and the energy integration of the measured charge-exchange neutrals multiplied by the plasma duration $\int \Gamma_{\mathrm{CX}}\, \mathrm{d}E \cdot \Delta t_{\mathrm{plasma}}$. The charge-exchange neutral flux is integrated with the energy from a few hundred eV to 30 keV based on the energy spectra shown in Fig. 3. The results obtained in the cases of changing the plasma duration are also plotted in the figure. A fairly good linear relationship is obtained. The above results are confirmed to continue without regeneration of CSP during the plasma experiments of more than one week ($\geqslant$ 300 shots), which corresponds to $\sim 2 \times 10^{16}$ H atoms/cm^2. CSP is hence effective on recycling control in the central cell of GAMMA-10.

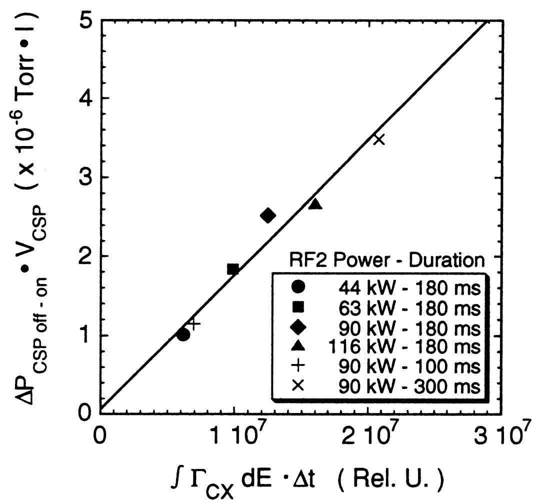


Fig. 5. The pressure-difference between CSP-on and -off $\Delta P_{\mathrm{CSPoff-on}}$ multiplied by the volume of the CSP test chamber V_{CSP} versus the energy integration of the measured charge-exchange neutrals.

4. Result of thermal desorption experiments

After exposed to charge-exchange neutrals, CSP is degassed by the direct Joule heating and the desorbed gases are analyzed with the QMA mounted on the test chamber. Fig. 6 shows the partial pressures measured after one-day exposure of plasma discharges. In this case the total duration of the plasma discharge is calculated to be about 12 s (0.2 s × ~60 shots). The temperature of the CSP increases up to ~450°C in 30 s after the onset of Joule heating and the peak of the partial pressures in mass numbers $m/e = 2$, 15, 28 and 44 are observed at that time. The predominant partial pressure is found to be hydrogen molecule and the observation of hydrogen and methane molecules during outgassing are consistent with the result obtained in the hydrogen glow discharge [5]. The above results are compared to those obtained in the case with CSP-off under the same vacuum condition of plasma shots. It is found that the ratio of the integrated outgassing rate of hydrogen with CSP-on is estimated to be larger than that with CSP-off by roughly 25–50%. A significant difference between CSP-on and CSP-off in the partial pressures of other gases, such as methane molecules, etc. has also been confirmed.

5. Conclusions

A small scale of pump module by using a carbon material (CSP) for the control of hydrogen recycling was manufactured and installed in the GAMMA-10 tandem mirror device. A significant difference between CSP-on and CSP-off was observed under good reproducibility and the difference became larger with the increase of the ICRF power. The phenomena that indicate the pumping ability of CSP were observed to continue during more than 300 plasma shots and there was no degradation in the pumping characteristics observed. Thermal desorption experiments after being exposed to charge-exchange neutrals provides that the dominant desorbed gas component is hydrogen. The above results show the effectiveness of CSP on controlling hydrogen recycling in actual plasma devices.

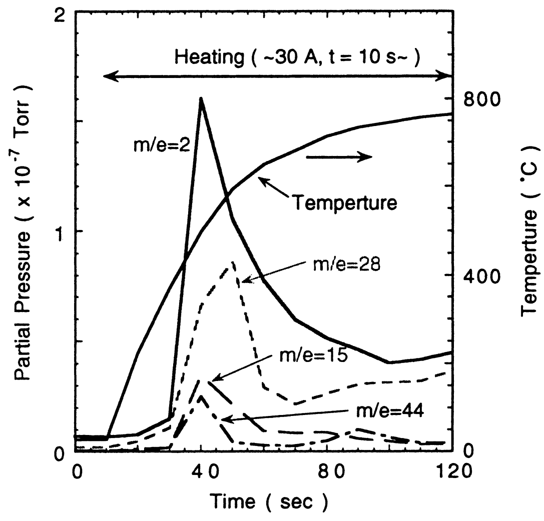


Fig. 6. The results of the thermal desorption experiments under one-day exposure to plasma discharges.

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