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Surface analysis and a novel application of carbon sheet pump in the GAMMA 10 tandem mirror

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Abstract

Samples of carbon sheet pump (CSP) exposed to fast neutrals have been analyzed by using microscopic techniques in order to improve the performance of CSP and to examine the applicability of CSP to actual devices. It has been confirmed from the microscopic viewpoint for the first time that fast neutrals emitted from plasmas generated by the actual confinement device (GAMMA 10) are trapped by the C/C material. A numerical simulation is performed by means of the Monte Carlo simulation code TRIM (ver. TRVMC95) for the sake of the evaluation of the results obtained by elastic recoil detection technique. CSP has been newly applied to the shine-through beam dump of a neutral beam injector in order to test the pumping effect of CSP under the conditions of high heat and particle load (several MW/m^2 and 2.5×10^{21} $H/m^2\,s$ at the beam center, respectively). It also has been found from pressure-balance analysis that 80% of incident particles are trapped by CSP.

Keywords: Plasma facing component; Hydrogen recycling; TRIM

1. Introduction

From the viewpoint of plasma control, reduction of hydrogen recycling is one of the most important subjects. Carbon sheet pump (CSP), which is developed for pumping in the divertor region of the Large Helical Device, is suitable for pumping fast neutrals under relatively low heat flux [1]. Almost all particles trapped in CSP can be desorbed in the regeneration experiment [1] in contrast to discharge cleaning which can only remove hydrogen and impurities adsorbed around the surface of the first wall. The hydrogen absorption capability (~5000 s in the GAMMA 10 central region) of CSP degassed by heating up to 800 °C is considered to be larger than that of the carbon wall conditioned by discharge cleaning. CSP is expected as a powerful method for the reduction of hydrogen recycling due to its small reflection coefficient until the carbon material is saturated with implanted hydrogen.

So far, the pumping effect of CSP on fast neutrals has been confirmed by macroscopic quantities such as hydrogen pressure in the test chamber [2]. Samples of CSP exposed to fast neutrals must be analyzed by using microscopic techniques in order to improve the performance of CSP and to examine the applicability of CSP to actual devices. It was confirmed that the pumping effect of CSP has no remarkable difference between room temperature and 200 °C as a result of our earlier work [3]. Heat and particle load to the first wall has a tendency to increase with improvement of plasma performance and extended pulse length. Therefore, CSP is newly applied to the shine-through beam dump of a neutral beam injector (NBI) as a high heat and particle

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source in order to confirm the operation region of CSP experimentally. In this paper, results of surface analysis of samples exposed to GAMMA 10 plasma and pumping characteristics of CSP under the condition of high heat and particle load (several MW/m^2 and 2.5×10^{21} H/m^2 s at the beam center, respectively) are described.

2. Surface analysis of CSP samples

2.1. Experimental and analysis technique

The surface station for exposing samples to fast neutrals is located in the central region of the GAMMA 10 tandem mirror [4]. Charge exchange fast neutrals of relatively high energy (0.5–5 keV) exist in this region [5]. Samples exposed to fast neutrals are the C/C material used as CSP in our test module and their size is $20 \times 10 \times 1.5$ mm^3. The samples are annealed at a temperature of 800 °C for 10 min before the exposure. They are analyzed by means of elastic recoil detection (ERD) and Rutherford backscattering spectroscopy (RBS) techniques using a several MeV helium ion beam [6]. The depth profile of the hydrogen density is measured with the ERD technique. Elements in the near-surface region can be identified by the RBS. The motivation of RBS is to investigate the existence of impurities from the plasma.

2.2. Results and discussion

The hydrogen depth profile of an exposed C/C material is different from that of an annealed one as shown in Fig. 1. The experimental data are noticeably scattered owing to the large surface roughness of C/C material and low fluence of fast neutrals. From the count number of recoiled atoms, hydrogen density in the material can be evaluated in this analysis. This difference is considered to be caused by fast neutrals trapped by C/C material. The pumping effect of CSP has been estimated by the pressure difference with and without CSP during plasma discharges. It has been confirmed from the microscopic viewpoint for the first time that fast neutrals emitted from plasmas generated by the actual confinement device (GAMMA 10) are trapped by the C/C material.

Fig. 2(a) shows the RBS energy spectra of exposed and annealed C/C materials. The channel number depends on the backscattered helium energy and the depth of the target atom. Both spectra roughly overlap each other. As shown in Fig. 2(b) (magnified figure of high-energy side), a minute amount of oxygen (<1%) has been detected on the surface of the exposed sample. However, probably no serious problem occurs for the pumping performance of CSP because the analysis was conducted after ventilation and the quantity of oxygen was significantly smaller compared with that of carbon.

Numerical simulations in which a carbon material is exposed to the Maxwell-distributed ion flux are carried out by means of the Monte Carlo simulation code TRIM (ver. TRVMC95) for comparison with the ERD results [7]. Ions are used as a substitute for fast neutrals in the numerical calculation. It was found that the energy spectrum of the charge exchange fast neutral emitted from the GAMMA 10 plasma is expressed as a superimposing of a Maxwell-distributed low temperature bulk component (~90%) on a Maxwell-distributed

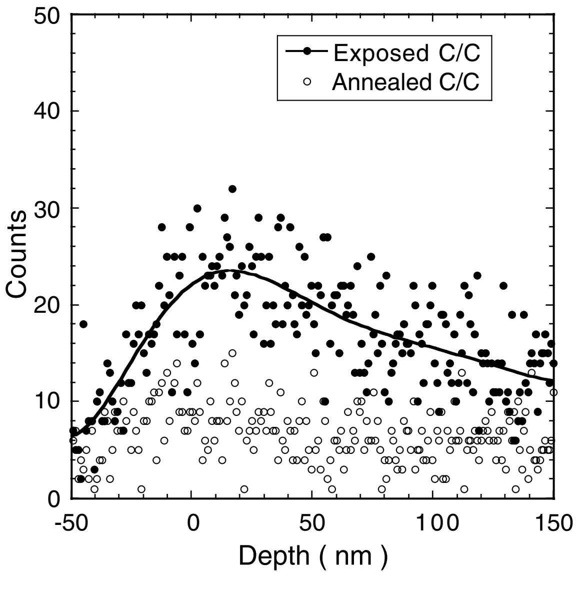

Fig. 1. Depth profiles of hydrogen density in the samples. Solid line is drawn to guide the eye.

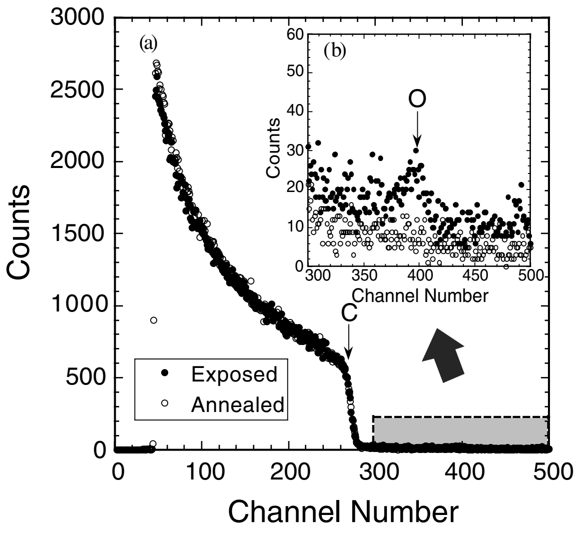

Fig. 2. RBS spectra of the samples. (a) Whole spectra, (b) a magnification of high-energy side.

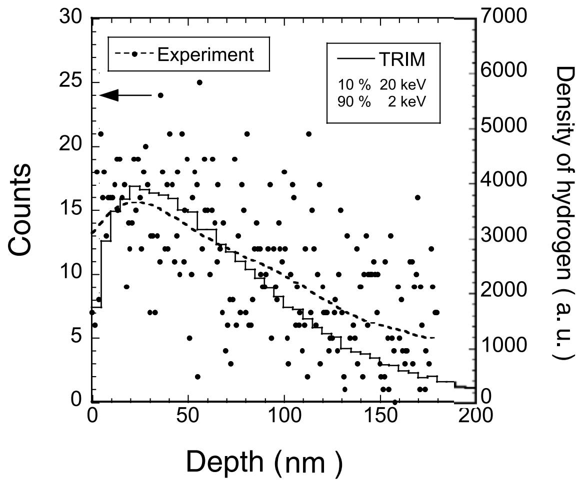

Fig. 3. Comparison between hydrogen density due to fast neutrals and the calculation result by using the TRIM code.

high-energy tail (~10%) [5]. The calculations are performed taking into account these two components. The experimental result qualitatively agrees with the numerical calculation at the bulk ion temperature of 2 keV and the tail temperature of 20 keV as shown in Fig. 3. Circles show the count obtained by subtracting the count of the annealed sample from that of the exposed sample in order to estimate the hydrogen density due to fast neutrals. The ion temperature of 2 keV also agrees with a typical bulk ion temperature of GAMMA 10 plasmas (0.5–5 keV). It seems that projectiles come to rest and are trapped by carbon near each projected range. In order to evaluate the hydrogen density quantitatively, we must consider hydrogen transport in samples using mass-balance equations proposed by Morita [6].

3. A novel application of CSP

3.1. CSP for NBI system

A NBI ($E_{inj} = 25$ keV) was recently installed in the central region of GAMMA 10 for plasma heating and fueling [8]. Due to the low line density of the GAMMA 10 plasma ($\sim 5 \times 10^{13}$ cm^{-2}, $T_e \cong 80$ eV), about 95% of the incident neutral beam (NB) passes through the plasma column in the present GAMMA 10 [9]. The amount of gaseous hydrogen caused by the shine-through beam cannot be ignored in the dump tank. The purpose of the CSP beam dump (CSPBD) is not only to examine the pumping effect under the conditions of high heat and particle load but also to reduce the backward flow gas to the central cell by pumping. Although CSPBD is a prototype of CSP, it is used as a powerful pumping device in GAMMA 10.

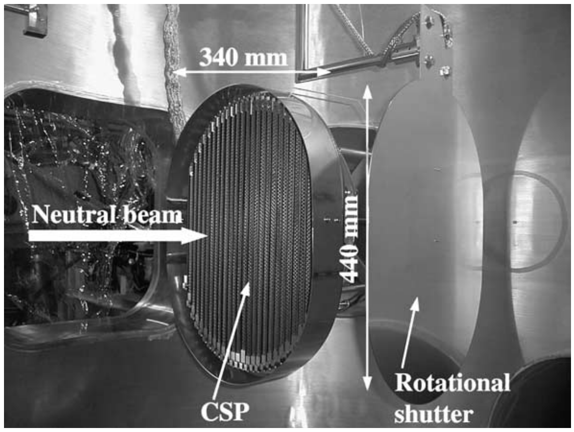

Fig. 4. A photograph of the CSPBD on the basis of the thermal design.

A photograph of CSPBD produced on the basis of the thermal design is shown in Fig. 4. CSPBD consists of 50 strips of C/C sheet of 11 mm in width and 1.5 mm in thickness, the length of which are various sizes (250–400 mm). The strips incline at 60° to the incident beam in order to reduce the heat flux. Each strip is electrically connected in series and CSPBD is heated up to ~700 °C in the regeneration experiment. In front of CSPBD, a rotational stainless shutter which intercepts the NB is mounted. The pumping effect of CSP can be examined by the use of this shutter (CSP-on and CSP-off). The flux at the beam center of NB (2.5×10^{21} H/m^2 s) is approximately one thousand times larger than that of fast neutrals emitted from the GAMMA 10 plasma ($\sim 10^{18}$ H/m^2 s). This enables an examination of the pumping effect of CSP in the high flux circumstance. The pressure rise caused by NB is measured with a fast ionization gauge.

3.2. Pumping experiment

Fig. 5 shows the result of the pumping experiment in which a shine-through beam is incident on CSPBD. It has been found that the pressure of CSP-on is lower than that of CSP-off in the experiment with a 20 ms pulse length of NBI. It has also been confirmed that the pressure of 30 ms of CSP-on is lower than that of 20 ms of CSP-off before ~400 ms. These results indicate that CSPBD has a pumping effect on NB.

A pressure-balance analysis is conducted in order to evaluate these results quantitatively. The time evolution of pressure in the dump tank is expressed as follows:

$$V_{dump}\frac{dP_{dump}}{dt} = C(P_{CC} - P_{dump}) - S_{eff}P_{dump} + (1-\xi)\Gamma + Q_{wall}, \quad (1)$$

where P_{CC} and P_{dump} are the pressures of the central region and the dump tank, respectively. V_{dump} is the volume of the dump tank and S_{eff} is the effective

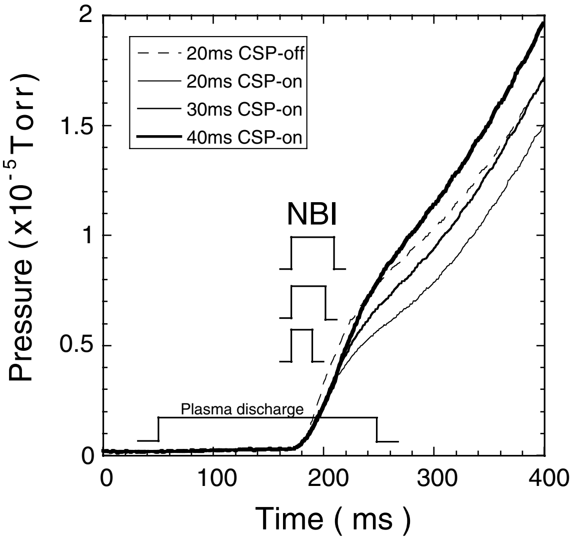

Fig. 5. Pressure rise at NB injection with and without CSP.

pumping speed of the pumping system in the dump tank. Γ is the flux of NB injected into the dump tank, ξ is the pumping efficiency of CSP defined as the ratio of number of trapped particles to that of incident ones, Q_{wall} is the gas flow from the wall of the dump tank and C is the conductance between the central region and the dump tank. The gas flow from the inner wall of the dump tank is estimated by substituting the initial pressures into the Eq. (1). Γ and $\mathrm{d}P/\mathrm{d}t$ are zero before the plasma discharge is initiated. It is assumed that Q_{wall} does not change during the plasma discharge.

Fig. 6 shows the correlation between the number of incident particles and that of trapped ones by CSP. The number of incident particles is estimated from the drain current of the ion source and the neutralization efficiency measured with the beam attenuation detector. The number of incident particles is proportional to that of trapped ones in the data of serial experiments shown as closed squares and closed circles. The data of the regeneration temperature of 700 °C are scattered to some extent because the data were obtained through the fluence dependence experiment. The data obtained through the fluence dependence experiment looks scattering since the pumping efficiency gradually decreases with increasing fluence. It has been experimentally confirmed that the pumping efficiency recovers to 0.80 from 0.69 by the regeneration. The beam center of CSP is considered to be saturated by the incident NB when this regeneration experiment was conducted. The fluence of the center is estimated to be approximately five times larger than saturation ($\sim 10^{22}$ H/m^2). The pumping efficiency of about 0.35 is obtained even in the case of CSP-off (beam is incident on the stainless shutter). The shutter is in front of CSPBD so as to protect the dump tank against the radiation from CSPBD in the regeneration experiment. The temperature of the shutter is heated up to around 500 °C during the experiment. The pumping efficiency of the shutter may be caused by the above baking effect and a low particle reflection coefficient due to high energy.

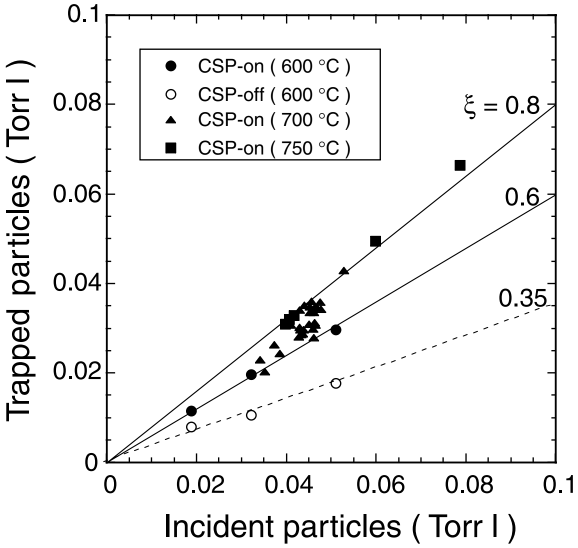

Fig. 6. The correlation between the number of incident particles and that of trapped ones by CSPBD. The temperatures in parentheses indicate the regeneration temperatures.

4. Conclusion

Samples of CSP have been analyzed by means of ERD and RBS techniques for the sake of improvement of CSP performance. It has been confirmed for the first time that fast neutrals emitted from an actual plasma are trapped in CSP by making a comparison between the hydrogen depth profile of the exposed C/C sample and that of the annealed one. The hydrogen depth profile caused by fast neutrals has been roughly explained by the result of Maxwell-distributed ion irradiation by use of the Monte Carlo simulation.

It has been found that CSP produced on the basis of the thermal design has a pumping effect under the conditions of high heat and particle load (several MW/m^2 and 2.5×10^{21} H/m^2 s at the beam center, respectively). It has also been found that 80% of incident particles are trapped by CSP as a result of pressure-balance analysis. The results obtained in the present work will be useful for the detailed design of CSP such as the estimation of lifetime in actual devices.

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