Development of a Compact Divertor Plasma Simulator for Plasma-Wall Interaction Studies on Neutron-Irradiated Materials

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We have developed a compact divertor plasma simulator (CDPS) that can produce steady-state deuterium and/or helium plasmas with densities above $\sim 10^{18}\,\mathrm{m}^{-3}$ for Plasma-Wall Interaction (PWI) studies of neutron-irradiated materials. The maximum particle flux is about $10^{22}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$. The CDPS was installed and is being operated in the radiation-controlled area of the International Research Center for Nuclear Materials Science, Institute for Materials Research, Tohoku University. We are able to control sample temperature within uncertainty of 5 °C during plasma exposure by adjusting the cooling air flow rate to the sample holder. The CDPS has a sample-carrier system, which makes it possible to transfer a plasma-irradiated sample from the sample holder to an infrared heater for analysis using thermal desorption spectroscopy (TDS) without exposing it to the air. This avoids the oxidation of the sample and minimizes the time between the end of plasma exposure and TDS analysis. An ITER-like tungsten (W) sample (A.L.M.T. Corp.), which has been irradiated by neutrons to 0.06 dpa in a fission reactor, was exposed to a deuterium plasma in the CDPS. The experimental results clearly show that the total deuterium retention in the neutron-irradiated W sample increases significantly in comparison with a pristine W, as demonstrated by broadening of the TDS spectrum at high temperatures.

Keywords: plasma-wall interaction, divertor plasma simulator, neutron-irradiated material, hydrogen isotope retention

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1. Introduction

The understanding of the retention of hydrogen isotope in the plasma-facing wall and the process of releasing them from the wall are among the most important tasks associated with fuel (particle) control in nuclear-fusion power reactors. In particular, the accumulation of tritium (T) in the plasma-facing wall is an important issue for the safety of future fusion devices, such as ITER and DEMO.

At present, tungsten (W) is considered one of the most promising candidate materials for nuclear fusion reactors because of its high melting point, low sputtering yield and low tritium inventory. On the other hand, it is known that defects—such as atomic vacancies and voids in metals—act as trapping sites for hydrogen isotopes. Consequently, there are concerns that the amount of T retention in W may increase dramatically due to defects created by neutron irradiation.

As reviewed in [1], numerous deuterium (D) plasma irradiation experiments have been carried out using W samples in which defects have been introduced by heavy-ion beams simulating neutron irradiation. However, neutron irradiation causes uniform damage/trap creation in materials because of its uniform primary-knock-on-atom energy, while heavy-ion beams create defects peaked at a certain depth determined by the Bragg curve. For this reason, both the static and the dynamic characteristics of hydrogen-isotope retention in neutron-irradiated W may differ considerably from those produced by heavy-ion-beam irradiation.

Deuterium (D) retention characteristics—determined by exposing neutron-irradiated W samples to D plasmas—have been examined under the cooperative Japan-US programs TITAN and PHENIX. The experiments were conducted at the Tritium Plasma Experiment (TPE) [2] of the linear plasma device at the Idaho National Laboratory following neutron irradiation at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. The experimental results indicate that the D-retention characteristics of neutron-irradiated W are quite different from those of W damaged by heavy-ion beams [3, 4]. Therefore, it is necessary to continue systematic research on the hydrogen-

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isotope-retention characteristics of neutron-irradiated materials toward the DEMO design. However, the number of facilities that can carry out PWI studies on neutron-irradiated materials is very limited.

Linear plasma devices—so-called "divertor plasma simulators" (DPSs), which are able to generate high-density plasmas relevant to divertor plasma conditions in toroidal fusion devices—have been widely utilized to conduct PWI studies as well as for research on edge plasma physics in the divertor region. New DPSs (JULE-PSI [5], MPEX [6]) have been designed and are being constructed in large radiation-controlled area. However, because of cost and safety issues, it is difficult to build a new radiation-controlled facility with a DPS, so cost-effective alternative approaches need to be considered. For this reason, we decided to develop a compact DPS (CDPS) with the same performance characteristics as a conventional large DPS but which can be operated in limited space and using less electricity, in an existing radiation-controlled area. Our goal is to use the CDPS to conduct PWI research on neutron-irradiated materials.

The CDPS we have developed at Nagoya University was installed in the radiation-controlled room of the International Research Center for Nuclear Material Science, Institute for Materials, Tohoku University (hereinafter referred to as the "Oarai Center") [7]. The Oarai Center has a long history of conducting neutron-irradiation tests using samples from nuclear reactors overseas (e.g., Belgian Reactor-2 [BR2]) as well as from reactors in Japan (the Japan Materials Testing Reactor [JMTR], the Experimental Fast Reactor [Joyo], and the Japan Research Reactor [JRR-3]). Many neutron-irradiated W samples already stored in the Oarai Center can be used for PWI research. Further, the Oarai Center has various analytical instruments—such as a Transmission Electron Microscope, Scanning Electron Microscope, Three-Dimensional Atom Probe and Positron Annihilation measurement capability for neutron/plasma irradiated PFMs—which are available for use in the radiation-controlled area.

In this paper, we describe the CDPS we have developed and report first results from D-plasma-irradiation experiments on neutron-irradiated W.

2. Configuration of the CDPS

Figures 1 and 2 show a schematic view and a photo of the CDPS installed in the radiation-controlled room at the Oarai Center. The CDPS consists of two magnetic coils, a high-efficiency DC plasma source, a sample holder with air cooling and a sample-carrier system that is connected to an infrared heater for thermal desorption spectroscopy (TDS). The CDPS is about 1.7 m long, 0.8 m wide and 1.8 m high. It has smaller space requirements and lower electric-power consumption than conventional DPSs [8]. In the DC plasma source, high-density, steady-state plasmas can be generated by the Phillips Ionization Gauge discharge. The key components of the CDPS are described in the following subsections.

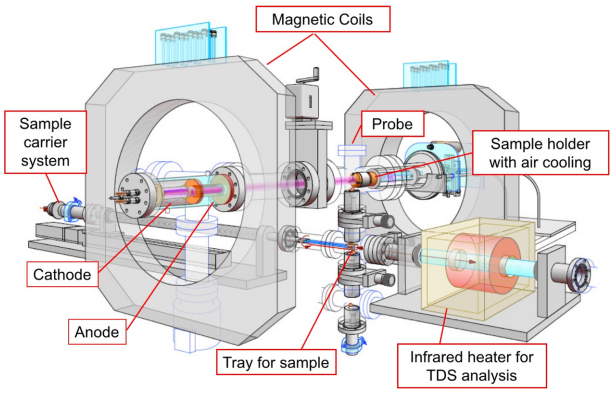

Fig. 1 Schematic view of the CDPS.

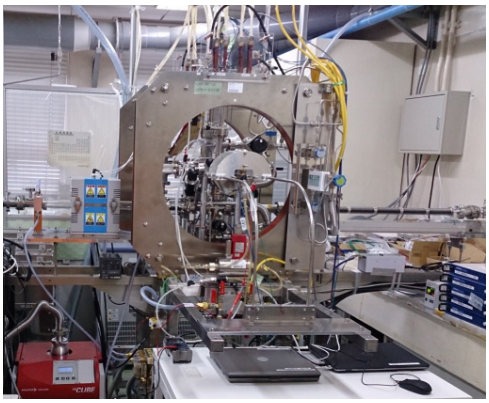

Fig. 2 Photograph of the CDPS installed in the radiation-controlled room at the Oarai Center.

2.1 DC plasma source and its performance for plasma production

The DC plasma source consists of a LaB_6 cathode and a water-cooled hollow copper anode as shown in Fig. 3. The plasma source is an improvement over that described in [9]. The two zigzag-shaped LaB_6 electrodes shown in the right-hand photo of Fig. 3 are connected in series and heated by a DC current. Each LaB_6 bar is 1.5 mm thick and 4 mm wide, and the bar is about 220 mm long. The LaB_6 electrodes can be heated up to 1600 K with a heating power of about 600 W (DC current is about 85 A). In contrast, a conventional DPS requires several kW to heat the LaB_6 cathode. The DC current heating of LaB_6 electrodes required by the CDPS contributes to its lower electric power consumption. Including the copper anode, the plasma source is 26.7 cm long and 11.4 cm in diameter. The compactness of the plasma source also contributes to the reduced size of the device. The LaB_6 electrodes are installed obliquely at a shallow angle with respect to the magnetic lines of force to form a V-shaped structure. This

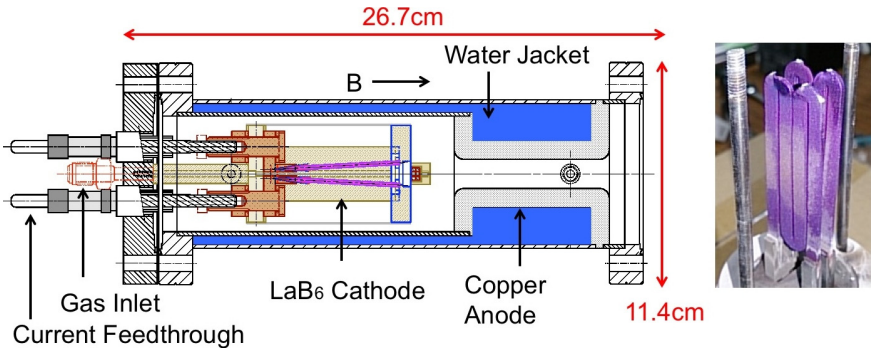

Fig. 3 Schematic view of dc plasma source.

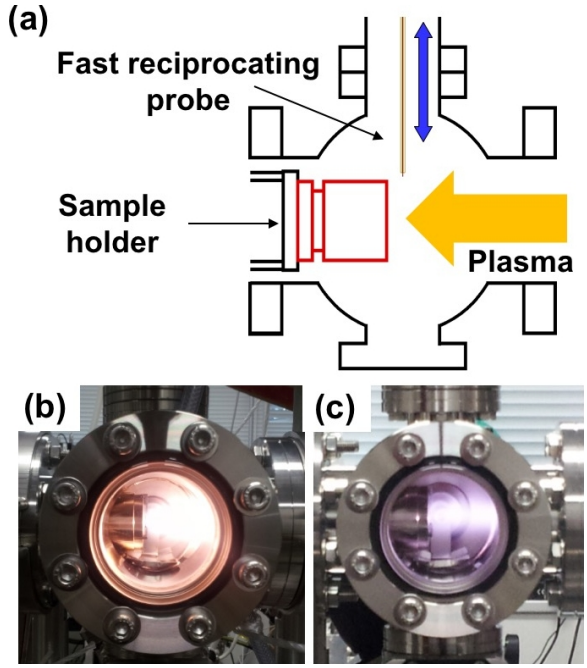

Fig. 4 (a) Schematic view of the sample holder. Photograph of generated helium plasma (b) and deuterium plasmas (c).

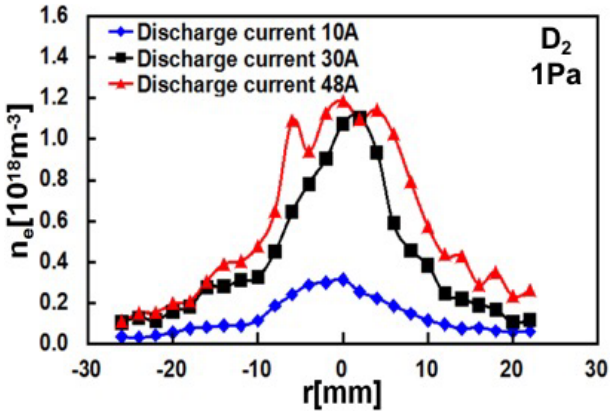

Fig. 5 Radial profiles of electron density in deuterium plasmas.

increases the effective cathode area, contributing to the high-density plasma production. The V-shaped LaB_6 electrodes are supported by a boron nitride structure and are surrounded by a cylindrical tantalum (Ta) plate for thermal shielding.

Five CV/CC programmable regulated DC power supplies (KIKUSUI Electronics Corp.), each having a 19-inch rack width with a 1 U height, are utilized for plasma production. One DC power supply (PWX1500L: 0–150 A, 0–30 V) is used for cathode heating, and two DC power supplies (PWX1500L) are used for the two magnetic coils. To conduct the plasma discharge, two DC power supplies (PWX1500MH: 0–20 A, 0–230 V) connected in parallel are used under master-slave parallel operation. All power supplies are controlled by LabVIEW software on a personal computer through a Ethernet connection.

Figure 4 (a) shows a schematic view of the sample holder. The photographs represent helium (He) and D plasmas generated by the DC plasma source described above. A fast reciprocating Langmuir probe is introduced into the plasma from the top of the vacuum vessel to measure the electron temperature and density as well as the plasma space potential. The W probe head with a diameter of 0.5 mm and a length of 2.0 mm, moves quickly up and down 9 mm away from the sample holder. Figure 5 shows plasma-density profiles measured in a D plasma as a parameter of the discharge current. The D gas pressure is 1 Pa and the magnetic field strength is 14 mT. The full width at half maximum of the plasma density is about 15 mm. The plasma diameter coincides with the inner diameter of the hollow anode. Uniform plasma irradiation can be realized for the W samples (typical diameter of a neutron irradiated W sample is 6 mm (or 3 mm) in diameter). The electron temperature distribution also peaks at the center; it is around 10 eV at the center and about 3 eV at the periphery. The plasma potential profiles, which depend weakly on the discharge current, are almost uniform in the radial direction; the potential is around −8 V at a discharge current of 48 A.

Figure 6 shows the discharge-power dependence of the electron density n_e and the electron temperature T_e at the centers of the D and He plasmas. As can be seen

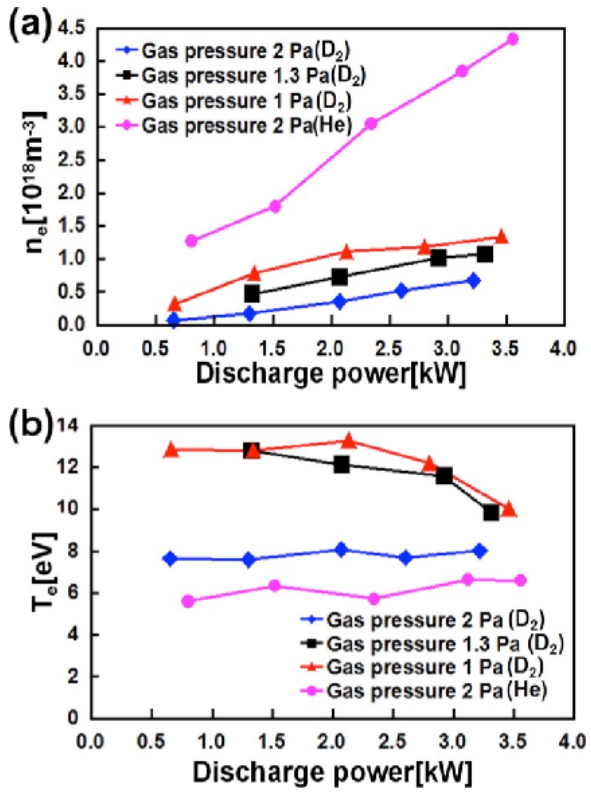

Fig. 6 (a) Electron density and (b) electron temperature as functions of the discharge power.

from Fig. 6 (a), the electron density n_e is roughly proportional to the discharge power. In the He plasma, n_e reaches 4.5×10^{18} m^{-3} at a gas pressure of 2.0 Pa and a discharge power of 3.5 kW, while the value of n_e in the D plasma is 1.2×10^{18} m^{-3} at a gas pressure of 1.0 Pa and a discharge power of 3.5 kW. We found that, in this gas pressure range, the lower the D gas pressure, the denser the plasma generated. On the other hand, T_e is almost constant, independent of the discharge power, except for the lower range of D gas pressure at large discharge power.

We conclude that high-density, steady-state plasmas similar to those in current DPSs can be generated by the DC plasma source in the CDPS.

2.2 Sample holder and sample-carrier system

Since the diffusion coefficients of hydrogen isotopes in materials are highly temperature-dependent, the sample temperature during plasma exposure—together with the plasma-exposure time—determines the diffusion depth of hydrogen isotopes in materials. Especially in neutron-irradiated materials, the total hydrogen isotope retention depends strongly on the diffusion depth because neutron-irradiated materials have uniform distributions of defects with depth. In order to establish a high-accuracy, hydrogen-isotope-retention database for neutron-irradiated W based on experimental results, precise control of the sample temperature is therefore required during plasma exposure. It is also necessary to use a miniaturized W sample such as 6 mm (or 3 mm) in diameter for neutron irradiation in fission reactors because W is highly activated by neutron irradiation, and it takes a long time before the radioactivity of a large W sample becomes low enough for it to be handled safely.

Figure 7 shows a schematic view and a photo of the sample holder installed in the CDPS. The sample is mounted on the center of the molybdenum (Mo) stage, where it is held securely by three movable Mo hooks. The Mo stage and hooks can be replaced easily for different-sized samples (3, 6, or 10 mm). The sample temperature is monitored with a tungsten-rhenium (5%Re-W26%), ceramic, sheath-type thermocouple. The head of the thermocouple couple presses gently against the back of the sample to guarantee a good thermal connection between the thermocouple and the sample. During plasma exposure, the sample temperature is controlled by adjusting air-flow rate, which can be varied from 0 to 200 L/min with a mass flow controller (SEC-E80: HORIBA STEC Co., Ltd.). The air-flow rate is adjusted to keep the sample temperature constant, using a feedback control that monitors the sample temperature measured by the thermocouple. The sample holder can be biased externally, using a bipolar DC power supply to control the energies of the ions incident on the sample.

In general, the sample temperature increases gradually toward the target value during plasma exposure, and the sample therefore has a history of plasma irradiation at temperatures different from the target value. In order to avoid this, we increased the sample temperature rapidly to the target value before plasma exposure, using electron bombardment caused by biasing the sample positively.

Figure 8 illustrates the procedure for transporting the sample from the sample holder to the infrared heater for TDS analysis. After plasma exposure, the three movable Mo hooks, which can be operated from outside the vacuum apparatus, are moved away from the sample-holder surface, and the sample is released and drops into the vacuum duct. The dropped sample is captured by a Mo tray located at the bottom of the vacuum duct. The tray is made of Mo because it is less likely to occlude hydrogen isotopes than are other high-melting-point metals such as Ta. The Mo tray is moved to a quartz-glass tube in the infrared heater, as shown in the photo in Fig. 8 by using a sample carrier system equipped with an electric linear actuator (IAI Corp., RCP3-SA6C-I-42P3-600-P3-S-B). After TDS analysis, the Mo tray is returned to the original position and is rotated to the upside-down position. The sample, then drops to the bottom of the vacuum duct, and it is removed from the vacuum vessel after closing the gate valve located above it. By utilizing this sample carrier system, it is possible to conduct TDS analysis for plasma-irradiated samples without atmospheric exposure, shortening the time from the end of the plasma exposure to the start of the TDS analysis.

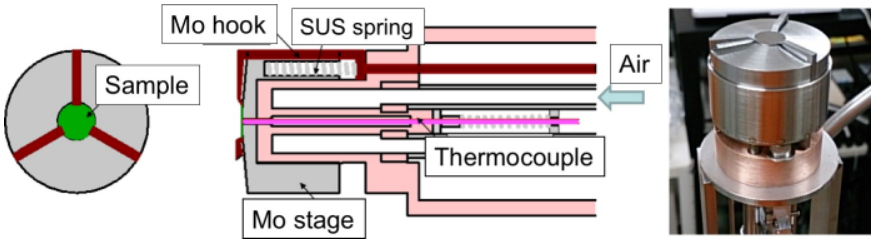

Fig. 7 Schematic view and photo of the air-cooled sample holder.

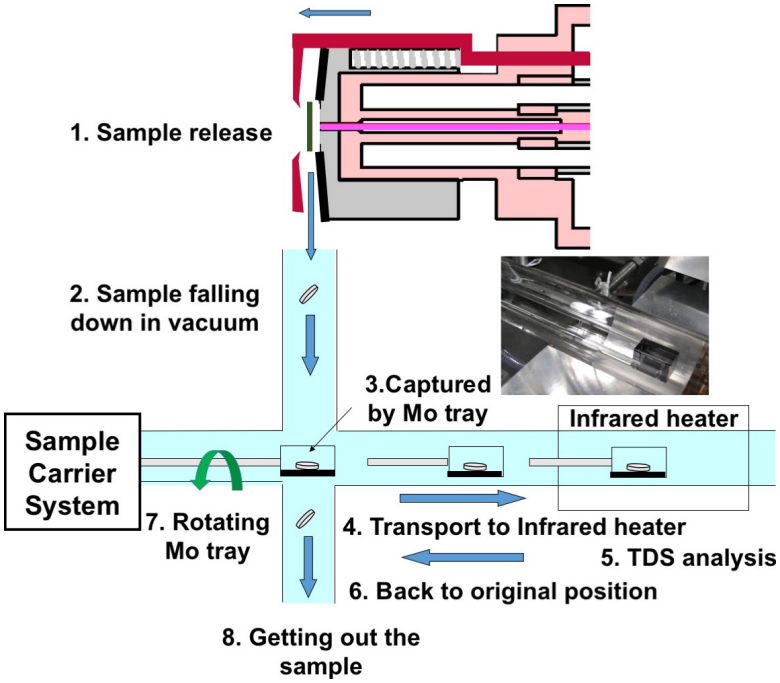

Fig. 8 Schematic diagram to explain how to transfer the sample form the sample holder to infrared heater for TDS analysis.

3. Deuterium-Plasma Exposure to Neutron-Irradiated W

We have conducted D-plasma exposures of neutron-irradiated W samples utilizing the CDPS we have developed. Two ITER-like W samples (A.L.M.T. Corp.), with diameters of 6 mm and thicknesses of 0.5 mm, were utilized in the experiment. One sample, annealed at 900 °C for 60 minutes, was irradiated by neutrons to 0.06 dpa in the fission reactor BR2 at the Belgian Nuclear Research Center at 290 °C. The surface of the neutron-irradiated W sample was electropolished before plasma exposure to remove contamination of the sample surface produced during neutron irradiation. Another sample, without neutron irradiation, was annealed at 900 °C for 30 minutes. Each W sample was mounted separately on the sample holder and irradiated by a D plasma in the CDPS. Figure 9 shows the time evolution of the W-sample temperature, as well as the cooling gas flow rate. Before plasma exposure, a low-density plasma was generated and the sample holder was biased positively in order to heat the W sample to the target temperature of 290 °C by electron bombardment.

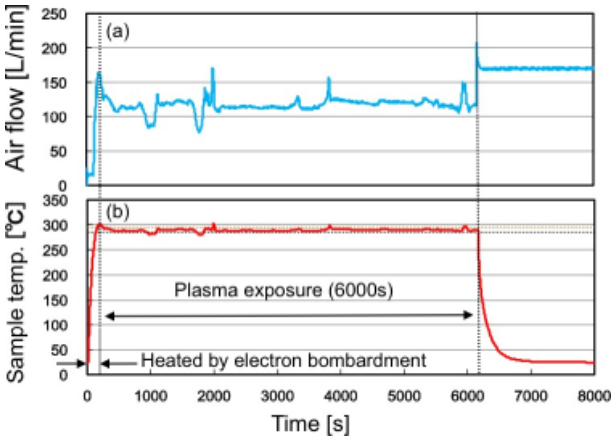

Fig. 9 Time evolution of air-flow rate (a) and sample temperature (b) in the experiment.

Once the sample temperature reached the target temperature, a high-density D plasma was turned on and the sample holder was biased negatively. Feedback control of the

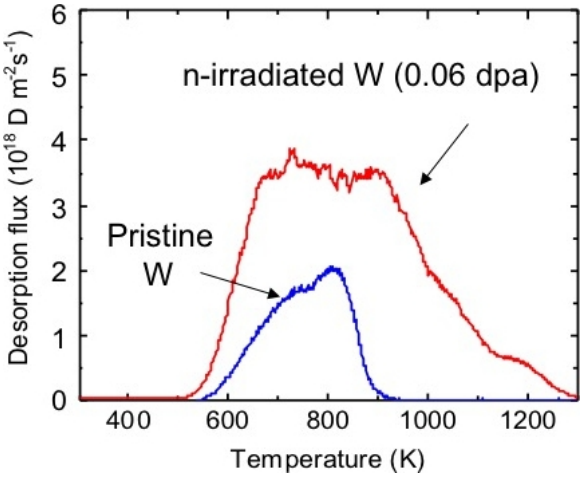

Fig. 10 TDS spectra of D-retained W with and without neutron irradiation.

air-flow rate was also started as shown in Fig. 9 (a). The deuterium ion flux was 5.4×10^{21} m^{-2}s^{-1} and the incident ion energy was about 100 eV, during the plasma exposure, which lasted 6000 s. Figure 9 (b) shows that the sample temperature during plasma exposure was kept constant at 290 °C within uncertainty of 5 °C by adjusting the cooling gas flow rate.

At 90 minutes after the end of the plasma exposure, the W sample was transported to the infrared heater, and the D retention was measured with TDS analysis with the rate of temperature ramp of 0.5 K/s. Figure 10 shows the TDS spectra of deuterium from neutron-irradiated W as well as pristine W. In comparison with the non neutron-irradiated W, the total D retention in the neutron-irradiated W is significantly increased, as indicated by the broadening of the TDS spectrum toward high temperatures: this was also observed in a previous study [3, 4]. The total amounts of D retention in the neutron-irradiated W and in the pristine W are 3.2×10^{21} D m^{-2} and 7.6×10^{20} D m^{-2}, respectively. This contrasts with the increase in total D retention for the neutron-irradiated W (0.025 dpa at 50 °C) that is shown in Fig. 1 of [3], which is significantly greater than our experimental result (0.06 dpa at 290 °C). Further, the peak of the TDS spectrum is shifted to higher temperatures in [3] than in our experimental result. The difference between these results is thought to be due to the difference in sample temperatures during D-plasma exposure (500 °C in [3] versus 290 °C in our experiment), because the D atoms are trapped in deeper defects at higher sample temperatures due to their large diffusion coefficients. Detailed experiments concerning the plasma exposure time and sample-temperature dependence of D retention in neutron-irradiated W are currently being conducted, and will be reported in the near future.

4. Conclusion

In this paper, we have described a CDPS that we have developed. It can be operated in a space-limited, radiation-controlled area and can generate high-density (above 10^{18} m^{-3}) D and He plasmas in a steady state, while maintaining precise control of the sample temperature during plasma exposure. The CDPS is equipped with a TDS apparatus, so that gas retention in samples after plasma exposure can be analyzed without atmospheric exposure. We have also reported the first experiments from D-plasma exposures of neutron-irradiated W samples that we have performed in the CDPS. The experimental results show a significant increase in the D retention of the neutron-irradiated W. At present, the CDPS is being widely used in collaborative research and a comprehensive PWI study of neutron-irradiated materials is underway.

Acknowledgments

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