KAERI divertor plasma simulator for studying material damage by deuterium ions and divertor cooling technique

Kil-Byoung Chai[1], Duck-Hee Kwon[1], Soohyun Son[2]
[1]*Korea Atomic Energy Research Institute*
[2]*Korea Institute of Fusion Energy*
kbchai@kaeri.re.kr

1. Introduction

The divertor concept has been widely used to achieve better core confinement in fusion devices. In the divertor configuration, open magnetic fields are subtended to the divertor target and therefore, high heat and particle fluxes come to the divertor targets along the magnetic field. In the ITER, the divertor targets are expected to experience 10-20 MWm^{-2} heat flux if the detached divertor is achieved. If not, the heat flux will be as high as 40 MWm^{-2} which is several times higher than the current engineering margin. Thus, it is urgently required to develop how to reduce the incoming heat and particle fluxes, how to increase the critical heat flux of the divertor system, and how to manufacture the divertor system that withstands extremely high heat and particle fluxes. This is so-called “divertor problem” and is one of the most challenging issues in fusion research.

In order to study divertor-related techniques such as divertor materials and divertor cooling techniques, the divertor simulators also known as linear devices are widely used. The typical particle flux of the linear device is $10^{22\text{-}23}$ $m^{-2}s^{-1}$ [1] and the typical heat flux is around 1–2 MWm^{-2}. Because the heat flux higher than the current linear devices is needed, we decided to use applied-field magnetoplasmadynamic (AF-MPD) thrusters instead. The AF-MPD thruster was chosen because it can produce a high-density plasma in cw mode which is necessary for achieving high heat flux.

2. Experimental setup

Two types of AF-MPD thrusters were developed and used in this work. The type I source (open type) with a wide thruster channel shown in Fig. 1(a) is used for heat flux test with Ar gas. The type II source (closed type) with a narrow thruster channel shown in Fig. 1(b) is used for ion flux test with H_2, D_2 or He gas. Both thrusters consist of copper anode, thoriated tungsten cathode, and ceramic insulators. An NdFeB permanent magnet is placed around the thruster body to provide the axial magnetic field. This axial magnetic field is necessary for AF-MPD thruster operation. Our magnet provides 0.17 T B-field at the center of the magnet.

We successfully ignited plasmas with H_2, D_2, He, Ar, and Xe gases. The plasmas are typically ignited at 600 V and initially show features of abnormal glow discharge, i.e. the plasma voltage is proportional to the plasma current. As increasing the plasma current, thermionic electrons are produced and the transition from abnormal glow discharge to arc plasma occurs. The details of the plasma current-voltage characteristics can be found in Refs. [2, 3].

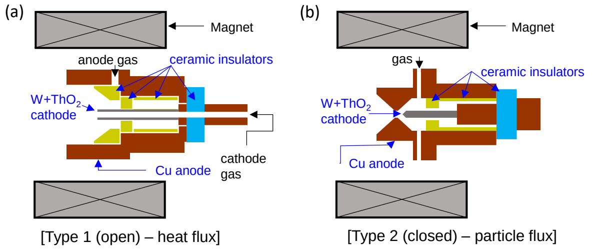

Fig. 1. Sketches of (a) type I and (b) type II sources in KAERI divertor plasma simulator.

3. Heat flux measurement

In order to measure the heat flux produced by our AF-MPD thruster, we built a custom calorimeter consisting of a copper block and a copper cooling tube. The spatial temperature profile of the copper block and the temperatures of inlet and outlet cooling water are measured. Then, the heat flux is obtained by using the heat conduction equation ($q = -\kappa\Delta T/\Delta x$ where q is the heat flux, κ is the thermal conductivity, T is the temperature and x is the position) and the calorimetric equation ($Q = cm\Delta T$ where Q is the heat energy, c is the specific heat).

Figure 2 shows the measured heat flux in our facility. As seen in the figure, the heat flux is proportional to the plasma current and inversely proportional to the distance between the plasma source and target. The maximum heat flux was obtained to be 10 MWm^{-2} when the plasma current is 200 A at 30 cm distance.

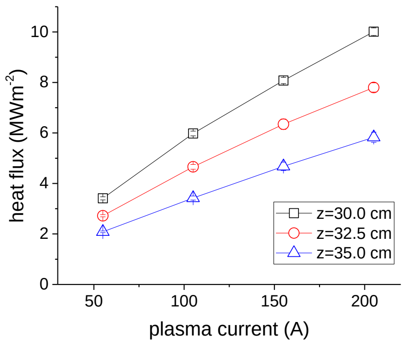

Fig. 2. Heat flux measured by custom-made calorimeter

4. Ion flux measurement

To measure the ion flux, a Langmuir probe is placed at the target position. Then, the ion saturation current, I_{is}, is measured by applying –200 V to the probe tip. The ion flux, Γ_i, is then calculated from the relation, $\Gamma_i = I_{is}/eA_{eff}$ where e is the elementary charge and A_{eff} is the probe tip area.

The measured hydrogen and deuterium ion fluxes are shown in Figs. 3(a) and (b), respectively. As seen in the figure, both hydrogen and deuterium ion fluxes are measured as high as 10^{23} $m^{-2}s^{-1}$. The hydrogen ion flux seems proportional to the plasma current while there is a mode change in the measured deuterium ion flux.

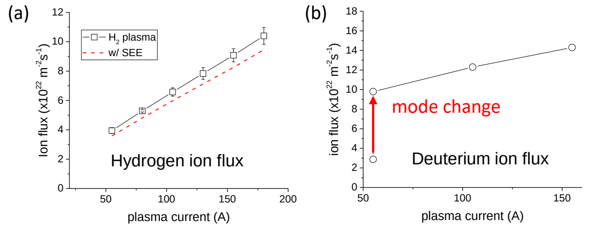

Fig. 3. (a) Hydrogen and (b) deuterium ion flux measured by a Langmuir probe. (SEE: secondary electron emission)

5. Study on tungsten damage by deuterium ions

After the KAERI divertor plasma simulator was developed, we have studied the blister formation on the tungsten after deuterium ions are irradiated. A tungsten sample holder was built as seen in Fig. 4 and installed at the target position. The tungsten sample is located at 35 cm apart from the plasma source. In order to control the sample temperature, the water cooling system is prepared. A thermocouple is installed on the backside of tungsten sample and a pyrometer (AE, IGA-6) is used to monitor the surface temperature of tungsten target. An IR camera (Fotric, 346A) is used to measure the temperature of insulators on the target (BN/Al_2O_3). The incident ion energy is controlled by the bias power supply and the ion flux and total fluence are measured in-situ using the Langmuir probe circuit.

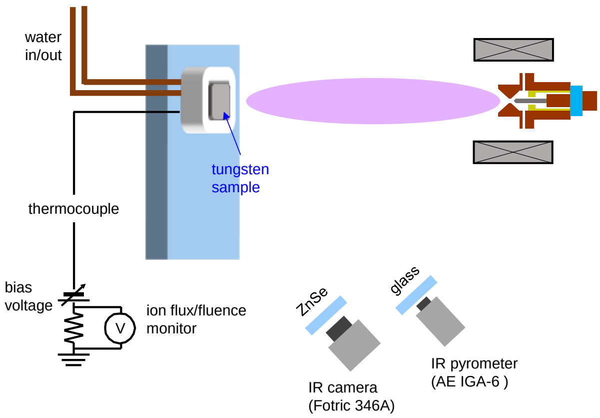

Fig. 4. Sketch of the D ion irradiation experiment.

Figure 5(a) is a photo of our beam irradiation experiment while Figs. 5(b) and (c) show the SEM images of before and after deuterium beam irradiation. As seen in Fig. 5(b), only the grain boundaries can be seen before the irradiation. On the other than, many blisters ranging between 500 nm and 1 μm are observed after the sample was exposed to deuterium ions. The incident ion energy is –100 V, ion flux (7–8)×10^{22} $m^{-2}s^{-1}$, and the total ion fluence was (3–4)×10^{25} m^{-2}. The temperature of the tungsten sample measured by thermocouple was 960 °C.

Recently, we vary sample temperature, incident ion energy, and tungsten makers and study the size and number density of the blisters formed on the tungsten sample. These data will be used to measure the emissivity of the tungsten in different surface condition.

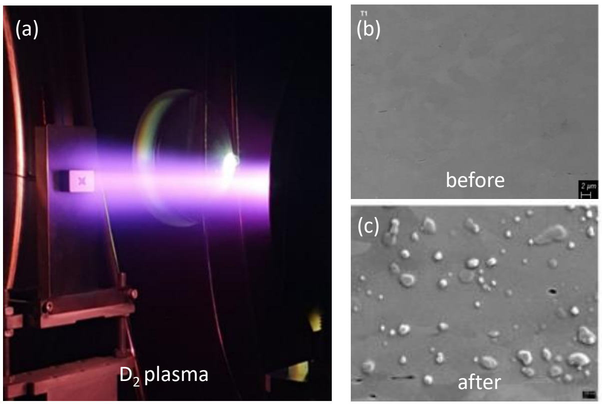

Fig. 5. (a) photo of actual experiment and SEM images of tungsten surface (b) before and (c) after deuterium ion irradiation.

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